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Volume 17 Number 8

BULLETIN
of the
AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS

AUGUST 1933

GEOLOGY AND OCCURRENCE OF NATURAL GAS IN AMARILLO DISTRICT, TEXAS[1]

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Amarillo, Texas, and Charleston, West Virginia

ABSTRACT

Natural gas is found throughout an almost continuous belt extending from central Beckham County, Oklahoma, northwestward to northern Moore County, Texas, and thence northward to and including Morton and Stevens counties, Kansas. This belt of productive gas territory is more than 200 miles in length and ranges from 5 miles to 40 miles in width and embraces an area of proved and semi-proved gas territory of more than 2 million acres, one of the largest and most important gas areas in the world. Gas is produced from beds of Permian and Pennsylvanian age. Accumulation of gas is closely associated with deposition and folding of these beds in relation to a buried mountain range known as the Amarillo Mountains. Natural gas has been known to exist in this area since 1918. From that time it has developed in economic importance until to-day it occupies first place in production of natural gasoline and carbon black and is rapidly becoming the largest producer of natural gas for domestic and industrial use. Natural gas is now being transported from this district by pipe lines to such distant points as Chicago, Indianapolis, Denver, and Fort Worth. The writers discuss the geologic occurrence of the gas and set forth production data in connection with its utilization.

ACKNOWLEDGMENT

The following geologists have contributed material or criticism in the preparation of this paper, to all of whom the writers express their appreciation: L. M. Oles of the Prairie Oil and Gas Company; J. D. Thompson, Jr., consulting geologist; W. E. Hubbard of the Humble

[1] Presented before the Association at the Oklahoma City meeting, March 24, 1932. Manuscript received, March 10, 1932. Preprinted from *Geology of Natural Gas*, a special symposium on world occurrence and geology of natural gas which will include authoritative papers on the gas fields of North America, Europe, and Asia. *Geology of Natural Gas*, now in manuscript form, will contain more than a thousand pages.

[2] Columbian Carbon Company.

[3] *Idem.*

Oil and Refining Company; T. F. Newman of the Skelly Oil Company; Frank T. Clark of the Empire Gas and Fuel Company; and Richard W. Camp of the Consolidated Gas Utilities Company.

INTRODUCTION

The Amarillo district embraces the Hugoton district of southwestern Kansas, the Oklahoma Panhandle, the Texas Panhandle, and the Sayre district of southwestern Oklahoma. This area, with the exception of the Sayre district, lies in the High Plains Province. The Sayre district lies just below the rim rock which borders the High Plains Province on the east. The High Plains Province is an almost treeless plain covered with alluvial deposits except along the larger streams where erosion has cut deep canyons in which the underlying Triassic and Permian strata are exposed.

Production of gas in this district is closely associated with a system of buried mountains or granite ridges extending northwestward from the Wichita Mountains of Oklahoma. The sedimentary formations which overlie these buried mountains have been folded into an arch over the granite core and form an immense anticlinal fold into which the gas and oil have migrated and accumulated. From the crest of the anticlinal fold the beds dip away northeastward into the Anadarko basin, southwestward into the West Texas Permian basin, and westward into the Dalhart basin. Separate domes and basins occur within the area, but these features are probably related to the principal mountain system. On the northwest insufficient drilling has been done to define clearly the limits of the district. Figures 1 and 2 set forth these relationships.

ECONOMIC HISTORY

Gas in this district was discovered in northern Potter County, Texas, in December, 1918. This discovery was on a surface anticlinal fold surveyed by Charles N. Gould, geologist, and called the John Ray dome. Drilling of the discovery well was recommended by Gould, and gas was encountered at a depth of 2,605 feet. The first commercial well in the Sayre district, Beckham County, Oklahoma, was completed in July, 1922, gas being encountered at a depth of 2,755 feet. Gas was discovered in Seward County, Kansas, in December, 1922, but not until May, 1927, when the first gas well of Stevens County was brought in by the Independent Oil and Gas Company at a depth of 2,617 feet, did this district become important. In 1925 and 1926 several gas wells were completed in Texas County, Oklahoma. All of the discovery wells were similar in that they started at or close to the

same geologic horizon, penetrated similar strata, and encountered the first showings of gas in the dolomite series of Permian age. This similarity was readily noted at the time but that these wells had roughly defined the extent of the immense gas field which we know to-day was not recognized until long afterward. They were considered to have opened separate and local fields.

The discoveries of gas in this district were made during the search for oil, and the finding of gas was not hailed with enthusiasm. The search for oil continued with the result that the proved gas areas have expanded to their present known limits. Only since trunk lines have been laid to distant markets has an effort been made to develop the gas reserves. Immense volumes of gas were encountered in wells which succeeded in producing oil. In the early development of the oil fields, little effort was made to conserve this gas and the wastage was enormous. Later the operators adopted conservation methods of drilling through the gas strata with less wastage of gas.

There are now eight counties in the Texas Panhandle from which gas is being marketed, while in four others gas has been found in commercial quantities. Gas has been found in two counties in the Oklahoma Panhandle, one of which is marketing its product. The Sayre district, in Beckham County, Oklahoma, has been marketing gas in limited quantities since 1923. The Hugoton district, in southwestern Kansas, has many shut-in gas wells which are being connected to trunk lines. Lines are now carrying gas from the Amarillo district to such distant markets as Chicago, Des Moines, Indianapolis, Denver, Midland, Wichita Falls, Enid, and Kansas City. This marketing development has taken place principally during the past four years. Lines under construction will soon extend the markets to include St. Paul and Minneapolis.

GEOLOGY PERTAINING TO OCCURRENCE OF NATURAL GAS

REGIONAL STRATIGRAPHY

Table I shows a correlation of geologic formations which are found in the Amarillo district and the neighboring districts. Gas occurs in the lowest formations of the Permian and the highest formations of the Pennsylvanian, these beds having been deposited in and along the southwest flank of the Anadarko basin and the north flank of the West Texas Permian basin. The Granite wash and the "Gray lime," both of Pennsylvanian age, show definite evidence of shore-line deposition. Along the flanks of the buried mountain range, there is a progressive overlap of formations against the granite core (Fig. 2). The "Gray

TABLE I

CORRELATION TABLE

	Eastern New Mexico		*Texas Panhandle*	*Western Oklahoma*	*Southwestern Kansas*
TERTIARY	Caliche				
					Cretaceous
TRIASSIC	Chinle Shinarump Moenkopi		Trujillo sandstone Tecovas shale		
PERMIAN	Red beds		Quartermaster	Quartermaster	Big Basin
	Rustler dolomite Salt series		Alibates Cloud chief	Cloud Chief Day Creek	Cloud Chief
	Anhydrite and sand		Whitehorse	Whitehorse	Whitehorse
	San Andres		Blaine	Dog Creek Blaine	Dog Creek Blaine
	Glorietta		San Angelo-Duncan	Chickasha-Duncan	Flowerpot Cedar Hills Salt Plains Harper
	Yeso		Salt series Red Cave	Hennessey-Garber	Hennessey Wellington
	Abo	"BIG LIME"	Anhydrite Dolomite	Wellington Stillwater	Wellington Marion Chase Council Grove
PENNSYLVANIAN	Magdalena	"BIG LIME"	"Gray lime" Granite wash	Wabaunsee	Wabaunsee
MISSISSIPPIAN (?)			Chert and siliceous limestone		Boone (?)
ORDOVICIAN (?)			Frosted sands, dolomite, and limestones		Simpson (?)

lime" is confined, except in the low gaps, to the flanks of the ridge, while the dolomite and anhydrite series, both of Permian age, were deposited over the mountain ridges. There are two known possible exceptions where the granite peaks are found in contact with the "Red Cave" and even in these localities there is evidence that the dolomite and anhydrite have been removed subsequent to deposition. There is an unconformity at the top of the anhydrite and possibly an unconformity at the top of the "Gray lime."

PRODUCING HORIZONS

The producing horizons of this district are the dolomite series of Permian age, the "Gray lime" of Pennsylvanian age, and the granite wash of Pennsylvanian age. Figure 2 shows cross sections of the gas-producing counties. These sections are built up from well logs and sample data and show the structural attitude of the producing horizons, erosional and depositional features and their relation to the granite ridge.

The most widespread gas-producing horizon is the dolomite series, which is productive in the higher portions of the Amarillo arch and northward across the Oklahoma Panhandle and into the Hugoton district of Kansas. This horizon consists of buff to white crystalline dolomite interbedded with gray shale. The dolomite has an oölitic phase throughout the Texas Panhandle, though in the Hugoton district sands appear locally at this horizon in this series.

The "Gray lime" is less widespread, being absent in the upper parts of the Amarillo arch, in the eastern counties of the Texas Panhandle, and in the Sayre district. In the western and northern counties of the Texas Panhandle this horizon is the source of the largest gas wells. Close against the Granite ridge it contains lentils of granite wash and in other localities it shows evidence of local fracturing, faulting, and solution cavities which when encountered yield the larger wells.

The Granite wash lies immediately over the granite mass except toward the basins, where it has been found to overlie beds of probable Mississippian or Ordovician age. Granite wash is the resulting material derived from disintegration of the granite mass following mountain-building movement. The granite gravels have been washed out from the main granite mass and have accumulated in the valleys and depressions and as alluvial deposits along the lower flanks of the mountain range. Local deposits of granite wash are found high on the granite slopes. Granite wash production is confined to the Texas Panhandle.

Gas wells have been found locally in fractures and the weathered surfaces of the granite core, the most notable being in Gray County, Texas.

STRUCTURAL HISTORY

It is agreed by those who have studied the Wichita Mountains of Oklahoma and the Texas Panhandle that uplifting of this mountain system has occurred at several periods since the first movement in early Pennsylvanian time.

The uplift in the early Pennsylvanian was followed by partial erosion of pre-Pennsylvanian sediments from the uplifted portion. A barrier was formed separating the Anadarko and West Texas basins. Deposition in these basins continued until, in the later Pennsylvanian, another uplift occurred along the mountain chain. Erosion following this movement completely denuded the granite ridge of Pennsylvanian and older sediments and the granite core itself was attacked by the forces of weathering and erosion. Oscillating shore-line conditions were brought into existence along the mountain front, and sands and arkoses from the granite ridge were being carried outward and intermingled with the shales and limestones being deposited in the basins. Arkosic limestones, shales, and dolomites are characteristic of the late Pennsylvanian sediments (Cisco-Wabaunsee) close to the Amarillo Mountains.

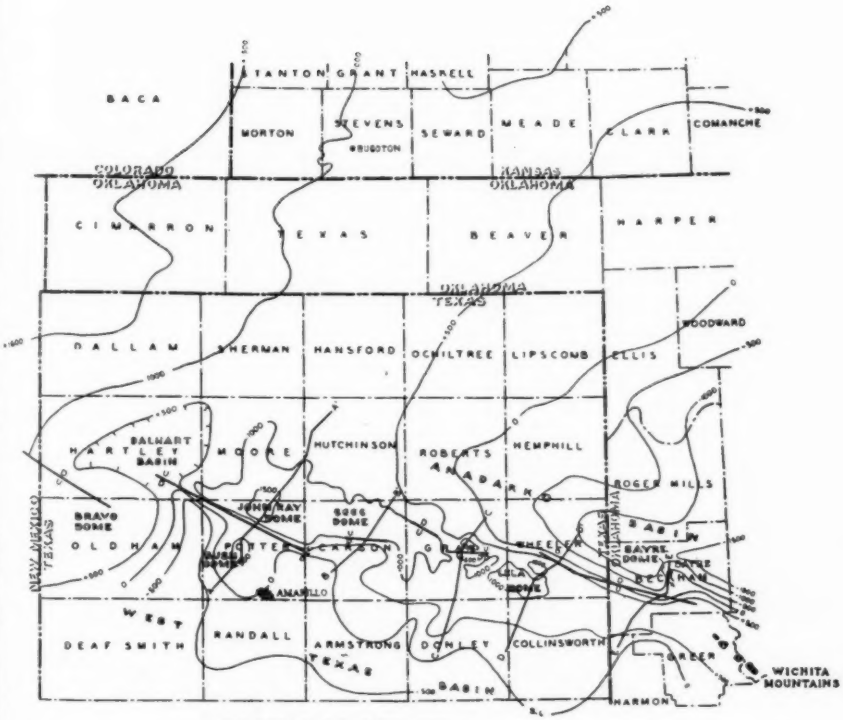
Interfingering of arkosic material with basin sediments continued during the subsequent deposition of Permian dolomite and anhydrite until the granite peaks were entirely covered. By this time all but the very highest peaks on the ridge had been covered by dolomite.

Following the deposition of anhydrite which marked the close of the "Big lime" time another upward movement of less magnitude occurred which was accompanied by faulting and folding of the sediments. Subsequent erosion removed the anhydrite and dolomite from the highest peaks and removed part of the anhydrite from less lofty parts of the buried mountain chain. This erosion is testified by finding pieces of anhydrite and dolomite embedded in the lower part of the "Red Cave" section near and on the highest peaks. The cross sections of Figure 2 show that faulting occurred following "Big lime" time. Increase of the throw of these faults with depth indicates that this faulting occurred in the granite basement rocks during earlier movements and that the later faulting had occurred along the old lines of weakness.

The arching of Permian and Triassic beds into the anticlinal fold which is superimposed above the Amarillo Mountains has been brought about largely through subsidence of the basins and compaction of the basin sediments. Lesser movements along old lines of weakness are also indicated as having taken place during and following the deposition of these younger beds.

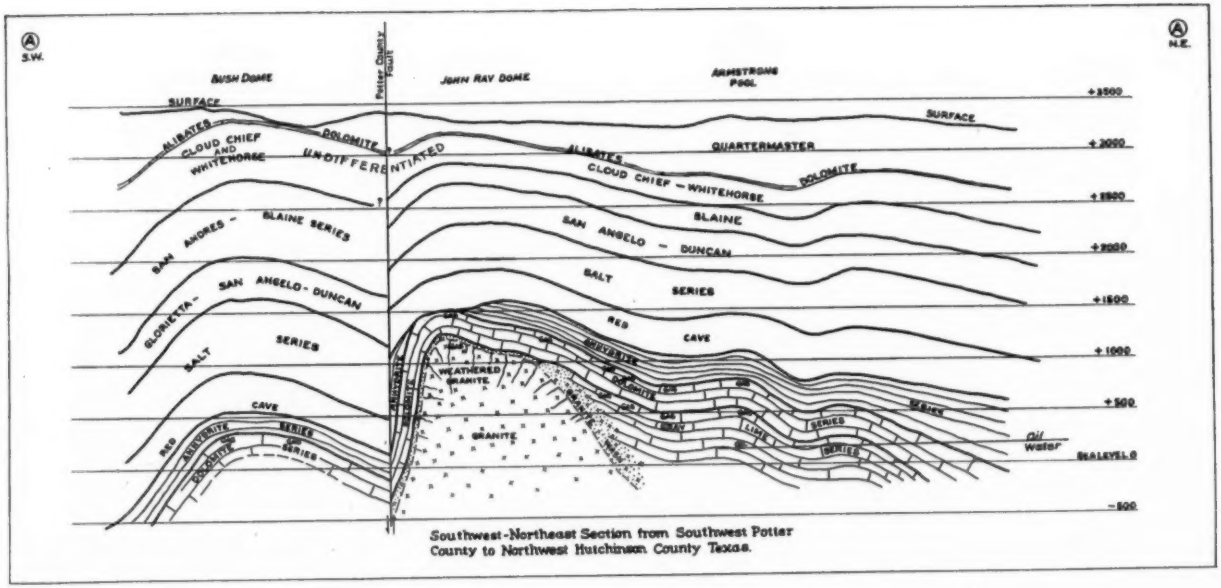
STRUCTURE

The structure of the sedimentary rocks which contain gas and oil in the Amarillo district consists of a broad arching of these beds over the buried Amarillo Mountains. Local structure is influenced by



STRUCTURE CONTOUR MAP OF THE AMARILLO DISTRICT BASED UPON THE TOP OF THE PANHANDLE BIG LIME
Contour interval 500 Feet
A——A Cross-Sections shown on Figure 2.
Faults

FIG. 1



Southwest-Northeast Section from Southwest Potter County to Northwest Hutchinson County Texas.

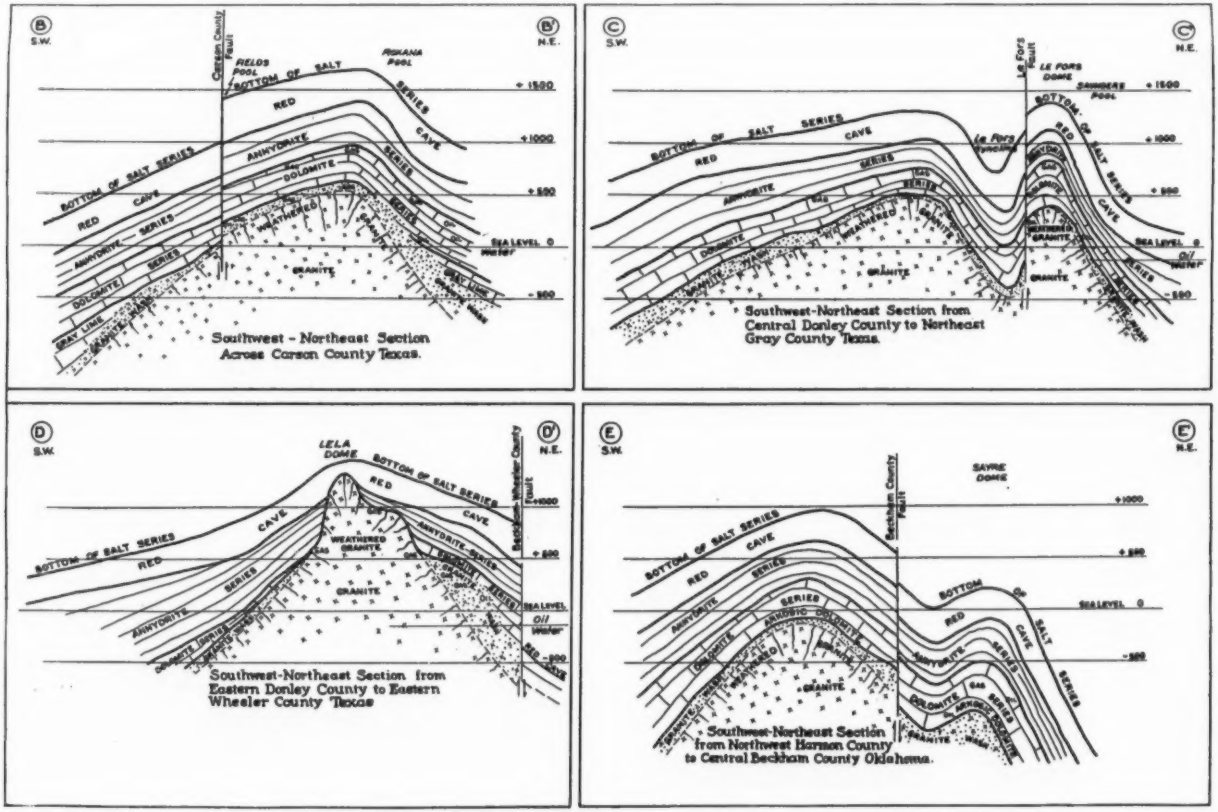

B
S.W.
B'
N.E.
Carson County Fault
REEDS POOL
PANHANDLE POOL
BOTTOM OF SALT
RED SERIES
CAVE
ANHYDRITE SERIES
DOLOMITE SERIES
BOTTOM OF SALT SERIES
GRAY LIME
GRANITE
WEATHERED GRANITE
+1500
+1000
+500
SEA LEVEL 0
-500
Southwest - Northeast Section
Across Carson County Texas.
C
S.W.
C'
N.E.
Le Fors Fault
LE FORS DOME
DUMMER POOL
Le Fors Syncline
Southwest-Northeast Section from
Central Donley County to Northeast
Gray County Texas.
D
S.W.
D'
N.E.
LELA DOME
Beckham County Wheeler County Fault
Southwest-Northeast Section from
Eastern Donley County to Eastern
Wheeler County Texas
E
S.W.
E'
N.E.
SAYRE DOME
Beckham County Fault
Southwest-Northeast Section
from Northwest Harmon County
to Central Beckham County Oklahoma.
SCALE
VERTICAL
HORIZONTAL

FIG. 2.

irregularities of the mountain range such as peaks, gaps, valleys, and fault scarps. The overlying sedimentary beds have been warped to conform with these irregularities upon which they have been deposited. The arching of the beds has been accentuated by successive uplifting of the mountains and by settling of the basins. Some minor folding along the flanks of the main uplift may be due to lateral pressures induced by the uplift of the ridge or by faulting at these periods. Figure 1 shows the regional structure of the district based on elevations on the top of the anhydrite series ("Panhandle Big lime"). Figure 2 shows cross sections of the various gas-producing counties.

It is a coincidence in the Amarillo district that the water level in each porous horizon occurs at or close to sea-level. Above the water level a band or zone of oil occurs and the upper portions of the anticlinal fold contain gas only. With this simple structural arrangement of the water, gas, and oil it is necessary only that the porous horizon lie above sea-level at the site of the test well in order to secure gas or oil production. The amount of production obtained in the proved area depends solely on the local porosity. Perhaps nowhere in the world is there an area of comparable magnitude in which oil or gas operators may proceed with their development with such assurance of obtaining the desired result. In the oil- and gas-producing counties of the Texas Panhandle, the ratio of dry holes to producing wells is 1:15; for the entire district, the ratio is 1:11. In the defined gas areas, the number of dry holes is practically negligible.

Along the general course of the main Amarillo anticline there are several local domes. The discovery well of the district was drilled on the John Ray dome in Potter County. The first oil well of the district was drilled on the flank of the 6666 dome in Carson County. The Le-Fors dome in Gray County is noted for its large gas wells, as is likewise the Lela dome in Wheeler County. Other domes which are closely associated with the main uplift are the Bush dome, in Potter County, which is noted for its helium gas production, and the Sayre dome in Beckham County. The last named domes are separated from the main uplift by faults as shown by the cross sections. The Bravo dome, in Oldham County, has been tested by drilling and found to be nonproductive of oil or gas. The "Big lime" is entirely missing, the "Red Cave" resting on the Granite wash. It is an accepted belief that the Bravo dome was a land mass during "Big lime" time. Minor folds and flexures occur along the flanks of the main uplift, notably in southwestern Hutchinson County and eastern Moore County.

In the northern Texas Panhandle, the Oklahoma Panhandle, and the Hugoton district of Kansas no anticlinal folding is known to

exist which is comparable in area or in structural relief with those here described. In these areas the structure appears to be monoclinal with the gas accumulating up-dip in porous dolomite or sandstones which lens out up the dip westward. However, further development of these areas and the drilling of magnetic "highs" may yet demonstrate some anticlinal folding.

In determining the location of buried granite ridges in this district the magnetometer has proved very accurate and, because of the close association of gas and oil occurrence with these granite ridges, this instrument has demonstrated its commercial value. Magnetometer surveys in the Amarillo district have not only delineated granite ridges, but they have also indicated the location of faults. The northern portion of the district has been mapped in great detail by the magnetometer, but insufficient drilling has been done to demonstrate whether the "highs" which have been found reflect the presence of similar granite ridges. South of the Amarillo Mountains several test wells have been drilled on magnetic "highs," but the drill failed to show other than normal conditions. Whether other influences than the granite basement were affecting the instrument or whether the interpretation of the readings in these early surveys was at fault is not known.

RESERVOIR ROCKS

The reservoir rocks of the gas and oil fields of this district consist of dolomite, limestone, sandstone, and arkose (granite wash). The dolomite is white to buff crystalline or oölitic. It occurs as a blanket formation over almost the entire district, retaining an average thickness of 250 feet. In a driller's log the first recorded showing of gas generally marks the top of this formation. Because of the variability in thickness of the overlying anhydrite series, geologists are noting carefully this datum point for constructing contour maps. The largest production comes from the oölitic zones. As shown by the cross section in Figure 2, the dolomite thickens basinward. The limestone is referred to locally as the "Gray lime." It lies next below the dolomite series in the geologic section. It does not produce oil or gas east of central Gray County, Texas. Production from the "Gray lime" is due to the presence of dolomitic and arkosic phases and to the occurrence of fractures. In Moore County this formation accounts for the oil production and for most of the gas production. This formation likewise thickens rapidly basinward.

The arkose in this district is known as Granite wash. It varies in character from fine granitic sand to large granite boulders. Where

most productive of gas and oil, it consists of coarse arkosic sand and gravel. Its porosity is highly variable along the flanks of the anticline, due to its being impregnated locally with red shales or lime cementing materials. Where no red shales or cementing materials are present, this formation is the most highly productive in the entire district. The gas of the eastern Texas Panhandle comes almost entirely from the Granite wash, because throughout most of this area the dolomite and "Gray lime" are missing at the gas-producing datum levels. The Granite wash is also important as a gas producer in northern Potter County. It is known to exceed a thickness of 700 feet locally.

Closely related to the arkose horizon, and difficult to distinguish from it, is the zone of weathered and fractured granite in place. A study of the granite surface at the outcrop in the Wichita Mountains of Oklahoma shows that weathering has produced a large number of fractures and joints in the granite and also that leaching out of the ferro-magnesian minerals has left cavities in the granite which are an ideal reservoir for gas and oil accumulation. Large wells have been encountered in this zone, notably in Gray and Wheeler counties.

A striking feature of the producing horizons is their remarkable continuity. The dolomite is practically continuous and its porosity is notably uniform throughout the area. The "Gray lime," although not present except locally over the ridges, produces gas or oil in a continuous band 60 miles in length. The Granite wash, although present only locally on the ridges, produces gas or oil in a continuous band for a distance of more than 70 miles.

RESERVOIR CAP ROCKS

The reservoir cap rocks of the Amarillo district may be classified as primary. Gas or oil is found in the dolomite when the drill has penetrated through the impervious anhydrite series. In the "Gray lime" producing horizon, the gas is found usually beneath a bed of shale or dense limestone which constitutes the cap rock. As a general rule, the upper part of the Granite wash contains beds of red shale and it is only after the drill has passed through these red shales that oil or gas is encountered. It would seem, therefore, that the cap rock beneath which oil or gas is found in this district is in its original state and has not been altered to its present impervious condition.

OIL

In this district oil occurs within the same reservoirs as the gas and water, there being no classification of "oil sands," "gas sands," and "water sands."

To date no oil has been encountered in the Hugoton district, and the Oklahoma Panhandle has had but one showing of oil, while the Sayre district had two or three commercial wells during its early life. The Panhandle of Texas has been a major oil-producing district since the fall of 1925. The oil is produced from twenty-seven localities or so-called "pools" distributed throughout a narrow band 90 miles in length and lying along the north flank of the Amarillo arch. One minor discovery of oil has been made on the south side of the arch in Carson County in close proximity to a probable fault. No oil has been found to date on the Bush dome in Potter County, but this is not conclusive evidence that oil will not yet be found on this fold. The encountering of a small quantity of oil in the dolomite close to the Potter County fault indicates that oil may yet be expected whenever further development is carried on.

MIGRATION OF OIL AND GAS

From the fact that the Anadarko basin contains carbonaceous formations in the Pennsylvanian and in the older Paleozoic rocks, though neither the presence nor absence of such beds has been demonstrated in the West Texas Permian basin adjoining the Amarillo Mountains, it is assumed that the gas and oil have migrated into the anticlinal folds from the Anadarko basin. The further fact that all of the important oil fields of the Texas Panhandle lie on the flank of the arch toward the Anadarko basin supports this view. The reservoir rocks are of late Pennsylvanian and early Permian age and the principal uplifting and folding of these beds has occurred at various times since early Pennsylvanian. Considering the origin of the reservoir rocks, it seems plausible to assume that the accumulating gas has displaced water within the reservoirs.

ORIGIN AND ACCUMULATION OF OIL AND GAS

Two sources for oil and gas in this area appear logical of assumption: (1) from source beds of pre-Pennsylvanian age and (2) from source beds of Pennsylvanian age.

That pre-Mississippian sedimentary formations are present on the north side of the Amarillo Mountains and close to them, is supported by the fact that outcrops of the Viola, Simpson, and Arbuckle are present at the surface on the north flank of the Wichita Mountains of Oklahoma, of which mountain system the Amarillo Mountains are the northwest extension. As further evidence of the existence of such beds, a well drilled by the Phillips Petroleum Company in the Borger field of Hutchinson County, Texas, passed through all of the Permian

formations, thence through the arkosic "Gray lime" and Granite wash of Pennsylvanian age and then passed through a thickness of 800 feet of chert, dark and greenish shales, sandstone, dolomite, and limestone. These sediments show some evidence of weathering. The abundance of chert suggests possible Mississippian origin while examination of the other material strongly suggests Ordovician origin. A few fragmentary fossils have been reported from this well, but there is no agreement as to their exact identification or age, varying opinions dating them from Mississippian to Ordovician.

From the foregoing it may be stated with some confidence that pre-Pennsylvanian beds exist on the north side of the Amarillo arch and dip rapidly into the Anadarko basin. If the Amarillo Mountains did not come into existence until early Pennsylvanian, we may assume that similar pre-Pennsylvanian sediments likewise exist in the West Texas Permian basin, but, due to the more gentle slope of the granite surface in that direction, erosion would have removed them to a position farther from the crest of the mountains. No sedimentary rocks of pre-Pennsylvanian age have been reported from wells drilled in this basin; in fact only the deepest wells which have been drilled far south of the crest of the mountains have succeeded in finding the "Gray lime" of Pennsylvanian age.

If the first source here proposed is correct, then the time of accumulation can be stated as having occurred no earlier than the time when the pre-Pennsylvanian beds were covered following partial erosion,—late Pennsylvanian. It would seem most logical to place this time of accumulation at the time of faulting and folding which followed "Big lime" time. At this period tectonic movements occurred and an overburden of several thousands of feet of sediments had accumulated over the supposed source beds in the basins. These two factors are popularly regarded as necessary in order that oil and gas be forced out of the source beds into a porous medium for migration and accumulation. The porous beds in this case are the granite sands which extend outward from the granite mass, the weathered and fractured surface of the granite, and the porous dolomite and limestone producing horizons which come in contact with it.

Should the second proposed source be correct, the same post-"Big lime" tectonic forces would be effective, but the influence of overburden in the basins would be less. That the tectonic forces following "Big lime" time were considerable is evidenced not only by the faulting, but by the folding of the Bush dome in Potter County and the Sayre dome in Beckham County. Smaller folds are known to exist in Moore and Hutchinson counties.

Both of the proposed sources for the oil and gas appear to be reasonable. It is significant that the oil and gas in the folds of northern Moore County and southern Hutchinson County have a high content of hydrogen sulphide and that the oil is found chiefly in the Pennsylvanian limestones which in these areas reach their maximum thickness. In Gray and Wheeler counties, where the Pennsylvanian limestones are absent, the oil and gas have very little or no hydrogen sulphide content and the gravity is about 10° higher. These circumstances suggest the Pennsylvanian as a source for at least part of the oil and gas in Moore and Hutchinson counties and the pre-Pennsylvanian as the source for the oil and gas in Gray and Wheeler counties.

It is a notable fact that no oil pools of importance have been discovered on the south side of the Amarillo arch. In this connection it is notable that this side of the arch is much less disturbed by faulting and folding and that the Pennsylvanian and pre-Pennsylvanian beds are further removed from the scene of the movements which took place near the crest and on the north side of the buried mountains.

VOLUME

Many wells capable of producing large quantities of gas have been drilled through the gas to the oil "pay." In the following tabulation, only wells completed as gas wells are listed. Wells have not been segregated as to the different zones from which they may be producing. Initial open flows of gas wells vary from two million cubic feet in a few small wells to wells in excess of 100 million. The production is dependent upon local porosity. Wells near to each other may vary considerably in open flow volume, but their rock pressures are the same. Certain areas develop large open flows, but almost in the center of such areas very small wells may be encountered, which is due either to a granite peak cutting out the porous zones or red shale cementing the Granite wash or the dolomite zone being less porous. The 703 gas

TABLE II

ANNUAL COMPLETIONS, TEXAS PANHANDLE

Year	*Number of Gas Wells*
1926 and earlier	62
1927	92
1928	140
1929	144
1930	169
1931	69
1932	27
Total to date	703

TABLE III

GAS WELLS IN PANHANDLE FIELD AS OF DECEMBER 31, 1932

County	*Number of Wells*	*Initial Open Flow Thousand Cu. Ft. Per Day*	*Average Open Flow Per Well in Thousand Cu. Ft.*
Carson	165	4,950,000	30,000
Gray	118	2,209,300	18,723
Hartley	7	119,500	17,100
Hutchinson	99	2,911,600	29,410
Moore	57	1,322,700	23,205
Potter	36	879,100	24,419
Wheeler	221	6,443,800	29,200
Total	703	18,836,000	26,793 average for field

TABLE IV

ESTIMATED GAS WITHDRAWALS FROM TEXAS PANHANDLE

Year	*Thousand Cu. Ft. by Public Utilities Companies*	*Thousand Cu. Ft. Casinghead Gas Treated for Gasoline*	*Thousand Cu. Ft. Casinghead Gas not Treated (Blown in Air)*	*Thousand Cu. Ft. Blown in Air During Drilling in Gas Wells*	*Thousand Cu. Ft Blown in Air During Drilling in Oil Wells*
1926 and earlier	15,725,533	34,300,000	92,000,000	17,200,000	88,200,000
1927	8,825,598	263,800,000	144,000,000	24,400,000	64,200,000
1928	39,978,176	330,500,000	114,000,000	30,000,000	19,500,000
1929	84,767,509	395,110,000	90,000,000	25,800,000	30,000,000
1930	81,175,878	412,796,000	70,000,000	27,800,000	24,800,000
1931	86,538,708	346,255,000	50,000,000	9,800,000	6,500,000
1932	97,168,645	281,524,155	32,940,000		
Total	414,180,047	2,064,285,155	592,940,000	135,000,000	233,200,000

Total estimated withdrawals from field 3,439,405,202 thousand cubic feet.

wells of the Panhandle district show an average open flow of 26.8 million cubic feet per day.

During 1931 there were 69 gas wells completed for an average open flow of 26,262,000 cubic feet per well.

During 1932 there were 27 gas wells completed for an average open flow of 23,215,000 cubic feet per well.

Annual withdrawal figures are not available in accurate amounts. Many statements have been made as to gas flowing to waste in the Panhandle field, but, due to the large area included in the drilling operations, the figures have probably been only a rough estimate. Table IV shows an estimate of the total gas withdrawn from the Panhandle field from its first development until January 1, 1933. The estimate presents an idea of the probable total amount of gas with-

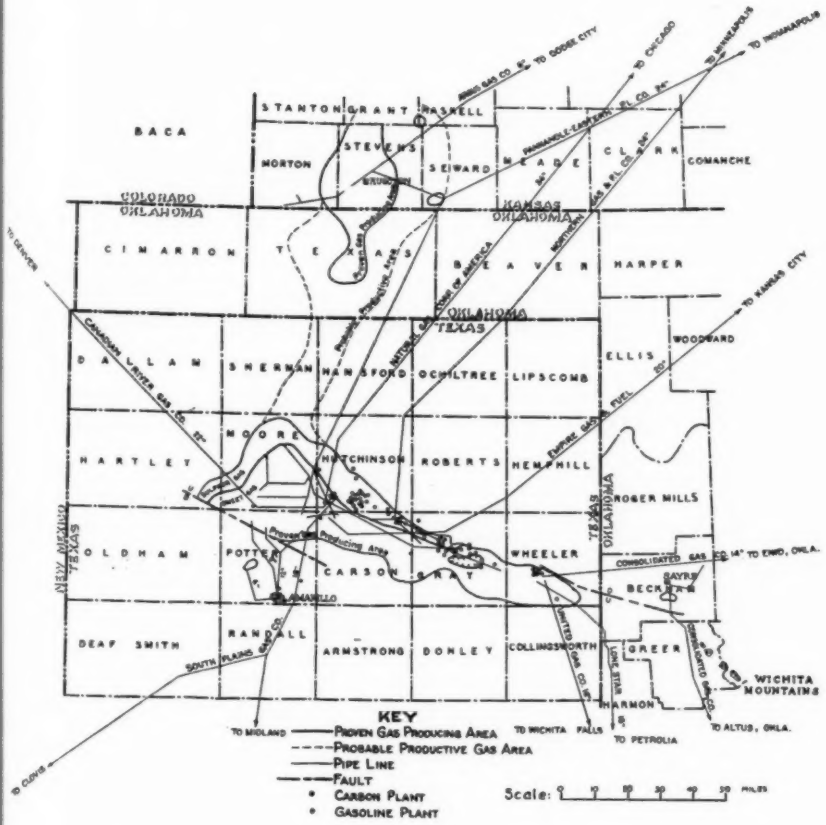

BACA
STANTON
GRANT
HASKELL
MORTON
STEVENS
SEWARD
KIOWA
CLARK
COMANCHE
COLORADO
OKLAHOMA
KANSAS
OKLAHOMA
CIMARRON
TEXAS
BEAVER
HARPER
OKLAHOMA
TEXAS
DALLAM
SHERMAN
HANSFORD
OCHILTREE
LIPSCOMB
ELLIS
WOODWARD
MOORE
HARTLEY
HUTCHINSON
ROBERTS
HEMPHILL
ROGER MILLS
OLDHAM
POTTER
CARSON
GRAY
WHEELER
BECKHAM
DEAF SMITH
RANDALL
ARMSTRONG
DONLEY
COLLINGSWORTH
GREER
HARMON
TO DENVER
TO CHICAGO
TO MINNEAPOLIS
TO INDIANAPOLIS
TO GOODE CITY
TO KANSAS CITY
TO CLOVIS
TO MIDLAND
TO WICHITA FALLS
TO PETROLIA
TO ALTUS, OKLA.
WICHITA MOUNTAINS
AMARILLO
KEY
PROVEN GAS PRODUCING AREA
PROBABLE PRODUCTIVE GAS AREA
PIPE LINE
FAULT
CARBON PLANT
GASOLINE PLANT
Scale:
MILES

FIG. 3

drawn from the field. Several of the items in the estimate are comparatively correct, but others are speculative and may vary considerably from the true amounts. Withdrawals by public utilities companies from 1932 show an increase over 1931 due to the completion of several major gas pipe lines during 1931. During the same period there has been a reduction in casinghead gas volume.

The producing area of the Texas Panhandle field is estimated at approximately 1,300,000 acres (Fig. 3). Of this amount, 100,000 acres has been drilled for oil production, although this has not been fully drilled up and may not all be productive of oil in paying quantities. Of the total gas area, that part on which initial volume of 10 million open flow per well or larger may be expected consists of approximately 896,500 acres. Initial volume contours of the field would show that a belt of small volumes extends around the outer edge of the producing area. Some small areas of less than 10 million volume exist within the larger open flow areas, being due to porosity factors previously mentioned.

PRESSURES

The rock pressure of Panhandle field is sub-normal, being less than half the normal hydrostatic head, and is uniform throughout the area, excepting the Bush dome in Potter County. The fact that pressure is equal and uniform in all productive zones indicates communication of the porous strata at the unconformity along the surface of the buried granite ridge.

The controlling pressure factor is not definitely known. The porous strata of the producing zones do not crop out at any known place in the form in which they are found in the wells. The character of the producing strata changes to shales and non-porous materials where their equivalents crop out. It is therefore assumed that at this time the producing zones are not exposed to a definite known hydrostatic head as a source of supply and that the pressure now existing was created when the producing zones were exposed to sea waters of former times. However, some geologists attribute the pressure to the hydrostatic head originating where the sedimentary rocks are in contact with the granite in the Wichita Mountains in Oklahoma at approximately 1,000 feet above sea-level.

The initial rock pressure of the Panhandle field was 430 pounds per square inch. Variations of 10 pounds have been noted on well completion records which may have been due to inaccurate gauges.

Decline in pressure is greatest throughout the areas developed for oil. This has been caused by the withdrawals of immense quantities

of casinghead gas as well as gas wasted when drilling through gas strata to the oil "pay." From the developed oil fields the pressure increases rapidly into the main gas-producing areas.

The following data give some idea of the present rock pressures in the gas-producing areas. The pressures were taken in June, 1931, at gas wells only.

Most of the rock pressures in the producing oil areas are considerably lower than those given in Table V.

The Bush dome in Potter County had an original rock pressure of 723 pounds. The pressure in December, 1931, was approximately 710 pounds.

TABLE V

County	*Maximum Pressure in Pounds*	*Minimum Pressure in Pounds*	*Number of Wells Gauged*	*Average Pressure in Pounds*
Carson	430	300	88	353
Gray	425	245	32	355
Hartley	426	425	4	425
Hutchinson	410	155	28	363
Moore	430	374	33	420
Potter	428	400	33	418
Wheeler	430	314	86	386

RECOVERIES

The great variation of open flow of wells in the Texas Panhandle indicates considerable differences both in porosity and thickness of the pay strata. Porosity is the main factor. This is probably substantiated from well-log records on pay thickness. Also with the different pay horizons it can readily be seen that estimates of reserves in the field should be calculated by the pressure-decline method. With this method it will prove difficult to obtain accurate results due to the fact that the area of the field is so large that simultaneous records of the wells are difficult to obtain as to withdrawals and pressures. Many estimates have been made on recovery per acre by engineers for the pipe-line companies, the more recent estimates ranging from 12 million to 17 million cubic feet per acre. In 1927 C. Max Bauer, assuming that the ultimate recovery would be 50 per cent, estimated the total recoverable gas in the reservoir at 4,436 billion cubic feet, but there are more data available at this time. Accordingly the Bauer estimate of total gas per acre was 9.2 million cubic feet.

As no water is present, on structure, in the gas pays or directly under them, the Panhandle field will no doubt have an ultimate recovery of all gas in the reservoir with the exception of a very small percentage.

It is now estimated that there are 896,500 acres in the Amarillo district in which wells will be completed with an average initial open flow of 10 million cubic feet or more; that the average thickness of "pay" is 65 feet; the average porosity is 20 per cent; and the initial reservoir pressure was 430 pounds per square inch. Reduced to a 2-pound base, the preceding data give an estimate of 15,289,000 cubic feet per acre, and an original reservoir content of 13,706,588.5 million cubic feet of gas.

In addition to the foregoing area, there are gas-bearing areas of smaller open-flow volumes and oil-field areas in the Amarillo district which must be considered. These areas are estimated to cover 403,500 acres. They include localities where wells are expected to produce less than 1 million cubic feet on completion. It is estimated that 6 million cubic feet of gas per acre will be recovered from these areas, giving an additional reservoir content of 2.4 trillion cubic feet, and a total original reservoir content of 16.1 trillion cubic feet of gas in the Amarillo fields.

The foregoing figures are simply an estimate and must be considered as such, but are given in order to show the tremendous amount of gas within this great reservoir.

If it is assumed that estimates of gas withdrawals in Table IV are approximately correct, there is now an approximate reserve of 12.7 trillion cubic feet of gas in the Panhandle field at this time, or about 79 per cent of the original amount.

Ultimate recovery per well will no doubt show marked variations. The following data are from a gas well in Gray County and are given as an example of recovery per well in an area where there are no near-by offsets. The records show that 4,327 million cubic feet of gas were withdrawn in a period of three years; rock pressure declined 20 per cent; and the open-flow volume declined 42 per cent. A gas well in Potter County has produced 14,840 million cubic feet of gas to date, while the pressure declined from 430 pounds to 395 pounds. A gas well in Wheeler County has produced 7,970 million cubic feet of gas to date. These wells are special cases and do not represent an average.

During 1931 the Panhandle field produced 21,137,355 barrels of oil. During 1932 it produced 18,014,920 barrels of oil, making a total to December 31, 1932, of approximately 194 million barrels of oil produced from this field.

UTILIZATION OF GAS

Table VI shows that approximately 4,200 miles of major gas pipe lines have been built to take gas from the Panhandle. This does not

include any lateral or branch lines. The major gas lines have an estimated daily capacity of 887 million cubic feet per day and the local lines a capacity of 80 million cubic feet per day, or a total pipe-line capacity of 967 million cubic feet per day.

TABLE VI

PIPE LINES OBTAINING GAS FROM PANHANDLE FIELD

Company	*Size in Inches*	*Length in Miles*	*Daily Capacity Thousand Cu. Ft.*	*Withdrawal for 1932 in Thousand Cu. Ft.*	*Terminal*
Amarillo Oil Co.	12	45	30,000	1,545,278	Amarillo, Tex.
Canadian River Gas Co.	22–20	340	125,000	12,170,499	Denver, Colo.
Central States Power & Light				504,172	Pampa, Tex.
Cities Service Gas Pipe Line	20	400	125,000	27,677,064	Kansas City, Mo.
Consolidated Gas Utilities	14	180	35,000	6,902,258	Enid, Okla.
Lone Star Gas Co.	18	200	50,000	7,318,658	Petrolia, Tex.
Natural Gas Pipe Line of America	24	925	175,000	26,198,952	Chicago, Ill.
Northern Gas & Pipe Line Co.	24–20	850	150,000	1,836,679	Rochester, Minn.
Panhandle-Eastern Pipe Line	24–20	1,100	150,000	2,449,215	Indianapolis, Ind.
Panhandle Power & Light Co.	8		10,000	279,181	Local—Towns in Panhandle district
Public Service Corp.	6		7,000	357,806	Local—Towns in Panhandle district
South Plains Pipe Line Co.	16	260	35,000	3,479,360	Midland, Tex.
Shamrock Gas Co.	6		8,000	138,529	Shamrock, Tex.
United Gas Co.	16–14	170	42,000	4,655,581	Wichita Falls, Tex.
U. S. Government	6		10,000	848,146	U.S. Helium Plant

There are several other smaller pipe-line companies serving local towns in the Panhandle district.

GASOLINE PLANTS

Most of the casinghead gasoline plants are of the absorption type and are operated on direct well pressures and by compressors. On January 1, 1931, there were 50 casinghead gasoline plants in the Texas Panhandle, estimated to have a daily capacity of 1,024,500 gallons and capable of treating 1,407 million cubic feet of gas daily.[4] There are also 5 gasoline absorption plants on natural gas lines in the district having a daily capacity of 357 million cubic feet.

[4] Editor's Note.—According to testimony at a hearing before the Texas Railway Commission at Pampa, Texas, February 15, 1932, about 1 billion cubic feet of gas is passed through natural gasoline plants daily. About 530 million cubic feet of the residue gas is used daily for the manufacture of carbon black and sold to gas transmission lines, and approximately 470 million cubic feet of residue gas is wasted to the air or burned by flares.

Not all plants are now operated at capacity. Because of the decline of flush oil production, and proration of oil properties, the casinghead plants operated at only ⅓ of their rated capacities during 1931. Gasoline recovery plants on natural gas transmission lines operate according to gas passed through the pipe lines.

TABLE VII

CASINGHEAD GASOLINE PLANTS IN TEXAS PANHANDLE

County	*Number of Plants*	*Daily Capacity in Gallons*	*Estimated Daily Capacity Thousand Cu. Ft. Gas*
Carson	9	86,000	177,000
Gray	19	522,500	558,000
Hutchinson	18	386,500	610,000
Moore	1	3,500	9,000
Wheeler	3	30,000	53,000
Total	50	1,028,500	1,407,000

LINE GASOLINE PLANTS (DRY GAS)

County	*Number of Plants*	*Daily Capacity In Gallons*	*Estimated Daily Capacity, Thousand Cu. Ft. Gas*
Wheeler	1	15,000	40,000
Potter	2	20,000	50,000
Moore	1	30,000	75,000
Hutchinson	1	75,000	192,000
Total	5	140,000	357,000

TABLE VIII

GASOLINE PRODUCED IN TEXAS PANHANDLE

Year	*Gallons*	*Estimated Total Thousand Cu. Ft. Gas*
1926	13,209,047	35,600,000
1927	97,105,711	269,500,000
1928	123,900,155	343,300,000
1929	206,885,321	419,700,000
1930	317,733,716	439,600,000
1931	270,260,000	374,700,000
1932	226,779,672	352,887,000
Total	1,255,873,622	2,235,287,000

CARBON BLACK

The large quantities of casinghead gas being produced from the oil wells in the Texas Panhandle created a favorable condition for the manufacture of carbon black. During the early development of drilling wells the gas was blown into the air and wasted. Gasoline extraction plants were soon erected to extract the gasoline from this casinghead gas. The residue from the casinghead plants was used for fuel on the leases, but this required only a small fraction of the total.

In September, 1926, the first residue gas was burned for the manufacture of carbon black. The carbon industry continued expansion during 1927, 1928, and 1929. The greatest construction program was during 1928. No new plants were built during 1931.

With the close of 1929 the production of carbon black had become equally as important, in the Texas Panhandle, as the production of oil and casinghead gasoline. At the close of 1930 there were 25 carbon plants in the Texas Panhandle with a combined daily capacity of 862,700 pounds of carbon black and capable of burning approximately 567,765,000 cubic feet of gas per day.

TABLE IX

CARBON BLACK PLANTS IN TEXAS PANHANDLE

Counties	*Number of Plants*	*Daily Capacity in Pounds*
Carson	2	86,800
Gray	8	301,400
Hutchinson	12	450,500
Wheeler	3	24,000
Total	25	862,700

CARBON BLACK PRODUCTION IN TEXAS PANHANDLE

Year	*Pounds Made*	*Estimated Amount of Gas Used in Thousand Cu. Ft.*
1926	2,566,000	1,890,000
1927	15,791,000	11,280,000
1928	60,228,000	43,020,000
1929	199,104,000	136,374,000
1930	254,844,000	168,104,000
1931	186,600,000	120,387,000
1932	177,812,000	118,591,000
Total	896,945,000	599,646,000

Carbon black plants in the Texas Panhandle comprise 58 per cent of the total capacity of all plants in the United States. In 1930 the Texas Panhandle plants produced 67.7 per cent of the total output of carbon black in the United States. About 1.5 pounds of carbon black are produced from 1,000 cubic feet of gas. Practically all of the plants are of the channel type. Only residue gas from casinghead gasoline plants is used in making carbon black.

COMPOSITION AND PROPERTIES

The composition of natural gas in the Panhandle fields varies to some extent according to the reservoir and locality. Table X shows representative analyses.

There are "sour" and "sweet" gases in the Texas Panhandle district. "Sour" gas is found largely in the lime producing areas of the Borger district. "Sour" gas is also produced by some wells in Gray,

Moore, Carson, and Potter counties. A "sour" gas contains from 5 to 200 grains of hydrogen sulphide per 100 cubic feet; a "sweet" gas contains 5 or less grains of hydrogen sulphide. Chemists state that most of the sulphur in the gas from the Granite wash zone is in the form of ethyl, prophyl, and butyl mercaptans rather than hydrogen sulphide. No "sour" gas is being taken by the pipe lines at this time.

The gasoline content of "lean" gas produced in the strictly gas areas of the Texas Panhandle varies somewhat. In general it can be stated that the lower a well is located on the north flank and the closer a well is to the oil-bearing areas, the higher the gasoline content of the gas. Natural gas delivered to transmission pipe lines in the Panhandle

TABLE X

ANALYSIS OF PANHANDLE GAS

	Composite Samples Wheeler County		*Gas Well Carson County*	*Composite Sample Casinghead Gas, Gray County*
	No. 1	*No. 2*		
Oxygen	0.22	0.40	0.40	
Carbon dioxide	0.00	0.10	0.30	
Nitrogen	1.59	2.10	1.80	
Methane	92.30	91.25	90.58	89.02
Ethane	3.09	2.80	3.70	4.02
Propane	1.81	2.09	1.37	4.20
Butane	.93	.82	1.08	2.90
Pentanes and heavier	.56	.44	.57	1.86
Gasoline content G.P.M.	.329	.307	.342	1.068

district has an average gasoline content of 0.33 gallon per 1,000 cubic feet of gas.

The gasoline content of casinghead gas varies greatly, and seems to be partially reflected by the gas-oil ratio. The average gasoline content is about 0.75 gallon per 1,000 cubic feet. It ranges from 0.36 gallon to 2.00 gallons per 1,000 cubic feet.

Natural gas from reservoirs on the Bush dome in Potter County contains 2 per cent helium. This gas is treated at the United States Bureau of Mines helium plant for the recovery of helium.

GAS-OIL RATIO

Oil wells in the Panhandle have no uniform gas-oil ratio. The oil wells produce varying quantities of gas with the oil depending upon casing points and whether the gas strata are in contact with or separate from the oil strata.

Gas-oil ratios vary from 500 cubic feet of gas per barrel of oil to more than one million cubic feet of gas per barrel of oil. Data compiled in 1930 gave the western part of the Texas Panhandle fields a ratio of 29,450 cubic feet of gas per barrel of oil and the eastern part

of the field a ratio of 9,780 cubic feet per barrel of oil. Average figures for such a large area may be in error. We do not feel that an average gas-oil ratio can be applied to the entire producing area or even to individual pools.

WATER

Surface water is generally encountered in the first 200 feet of formations drilled. Several other water-bearing horizons are encountered at various depths above the pay zones, depending on the location of the well. The first water-bearing horizon is encountered about 300–400 feet above the top of salt, and the second either in the top of salt or immediately above. No water is encountered from this last point to the oil-bearing horizons unless it is pocket water, but water is uniformly encountered at sea-level depths. This lower water is known as bottom or edge water and is encountered around the edge of the oil-producing area. Where encountered about sea level the reservoir yields water freely when penetrated. It is a saline water high in chlorides and also contains some sulphates.

STATUS

There is an oil-water contact in the oil-producing areas along the north flank of the Amarillo structure and a gas-water contact exists along the west and south edges of the field. This was the original status when drilling began and only the oil-producing areas have been seriously affected by water encroachment and coning. Very little lateral encroachment has occurred except in areas depleted of oil and gas. Coning is the greater trouble in the oil areas due to too rapid withdrawals of gas and oil. There being no bottom water present high on the structure in the gas-producing zones, no encroachment and coning of water can occur as a result of rapid withdrawals and thus cause reduction of pressure.

The water level occurs in each producing stratum at or near sea-level.

COMPOSITION

Table XI shows typical analyses of Panhandle field bottom-hole water in parts per million.

DEVELOPMENT

Both cable-tool and rotary drilling are common practice. General practice when using rotary equipment is to change to standard tools before drilling into the pay. Depths range from 1,400 feet to 3,200 feet, depending on location and whether drilling for oil or gas. Most of the gas is found at depths ranging from 1,400 to 2,900 feet.

The present pipe-line practice is intermittent withdrawals from gas wells.

Costs are dependent on location and depth. In Wheeler County it costs from $10,000 to $15,000 to drill and equip a gas well. In Moore County, where the wells are deeper, the cost ranges from $20,000 to $25,000 per well.

Gas wells are not tubed, but produce through the casing, usually 8¼ inches in size.

TABLE XI

WATER ANALYSES, HUTCHINSON AND CARSON COUNTIES

	Lime	*Granite Wash*	*Gray County Granite Wash*
Silica	80	48	50
Iron and aluminium oxide	62	540	108
Calcium	4,080	5,890	10,720
Magnesium	1,640	3,112	2,070
Sodium	52,200	48,210	48,800
Chloride	90,980	90,400	99,560
Sulphate	3,020	130	1,045
Bicarbonate	297	94	35
Total solids	152,359	147,424	162,388
Per cent total solids	15.2	14.7	16.3

The producing limits of the Texas Panhandle fields have been fairly well defined by drilling. The proved areas for oil and gas have not been fully developed. It is estimated that only ⅛ of the drilling has been done that will be required to fully develop the main gas areas.

In Wheeler County offsets of 660 feet accompanied the first development. Later practice adopted the proportion of one well to 40 acres but even this plan caused unnecessary drilling. The general practice now is to drill one well to 160 acres where leases will permit. This is also the general practice in Carson, Potter, and Moore counties.

HUGOTON DISTRICT

The limits of the gas-bearing territory in the Hugoton district, comprising Morton, Stevens, and Seward counties, Kansas, and Texas County, Oklahoma, have not been determined. Most of the gas wells in this area were drilled during the year 1930. Figure 3 shows the extent of gas-bearing territory according to present well data. The gas-producing area should ultimately extend over most of the probable productive area shown on Figure 3. It appears probable that the Hugoton area is continuous with the present proved areas of the Texas Panhandle, but lack of wells in the intermediate area prevents a

positive statement. The character of the producing zones and the interpolated structure lead to this conclusion. The most northerly well was completed in September, 1931, in the southwest corner of Haskell County, Kansas, for 14 million cubic feet per day in the same stratigraphic zone as the wells in Stevens County.

The gas in the Hugoton area is found at depths ranging from 2,500 to 2,800 feet in a porous dolomite containing some anhydrite. The producing zone is from 250 to 300 feet thick. The actual gas-bearing reservoirs in the dolomite zone are from 8 to 145 feet thick.

Initial open-flow volumes range from 1 million cubic feet to 22½ million cubic feet per day. The initial rock pressure was 440 pounds per square inch, uniform over the entire field.

By September, 1930, 73 wells had been completed with a combined open flow of 446 million cubic feet. The total open flow of the district on December 1, 1931, was 950 million cubic feet from 149 gas wells, or an average open flow of 6,378,000 cubic feet per well.

Sufficient data for determining gas reserves are not available at this time. Estimates of recovery, based on porosity and thickness of "pay," vary from 6 million to 8 million cubic feet per acre. As the thickness of the pay varies considerably from well to well, the pressure-decline method for calculating the reserve will be required for accuracy. As the necessary data are not yet available, we can only present estimates that may vary considerably from the ultimate recovery.

If an average thickness of "pay" of 50 feet, a porosity of 12 per cent, and an initial rock pressure of 440 pounds are assumed, the Hugoton district should produce 8 million cubic feet per acre reduced to 2-pound base. The present proved area shown in Figure 3 includes 388,000 acres, which should ultimately produce 3,124 billion cubic feet. The probable gas-bearing area in Stevens, Morton, and Seward counties, Kansas, and Texas County, Oklahoma, contains an additional 678,000 acres. The limits of the productive area have not been defined and the indications are that a much larger area appears favorable for gas production.

Utilization of gas from the Hugoton district is taking place through the following pipe lines: Panhandle-Eastern line, connecting the field near Hugoton to its main line near Liberal; Argus Gas Company, through its Dodge City system; Hardendorf Natural Gas line to Lamar, Colorado; Cimarron Utilities Company local lines in Texas County, Oklahoma.

During 1931 the withdrawals from the field probably did not exceed 18 million cubic feet per day, but this was increased in 1932

deliveries made to pipe lines of the Northern Gas and Pipe Line Company.

The estimated total gas withdrawals from the Hugoton field up to January 1, 1933, was 12,500 million cubic feet.

The gas produced is a sweet gas having a gasoline content of 0.225 gallon per 1,000 cubic feet. The B.T.U. content is reported at 1,100.

The wells are drilled to depths of approximately 2,500 feet with

TABLE XII

ANNUAL GAS WITHDRAWALS FROM SAYRE FIELD

Year	*Cubic Feet*
1923	292,007,000
1924	162,585,000
1925	92,739,000
1926	876,959,000
1927	1,173,602,000
1928	1,693,472,000
1929	1,952,304,000
1930	2,121,390,000
1931	3,799,593,000
1932	5,272,032,000
Total	17,436,683,000

rotary tools, and there changed to standard tools to drill through the gas-bearing rocks.

The cost of a completed gas well averages about $24,000. The wells produce from 6-inch casing. Only $\frac{1}{4}$ of the proved area has been drilled.

The customary practice of well spacing is one well to each 160 acres.

SAYRE GAS AND OIL FIELD

The Sayre oil and gas field is located in T. 9N., R. 23W., Beckham County, Oklahoma. Both oil and gas are found in this area on a small elongate dome, which is separated from the main buried granite ridge by a fault. The cross section of the field on Figure 2 shows the type of structure and position of the producing zones. The greater part of the development took place in 1923 and 1924. The average surface elevation is approximately 1,870 feet above sea-level. Drilling depths for gas range from 2,600 to 2,800 feet. The greater portion of the oil production was obtained at a depth of 2,960 feet in an area about 1 mile southwest of the gas-producing area.

Initial open-flow volume of gas wells ranges from 30 million to 40 million cubic feet per day. Initial rock pressure of the field was approximately 910 pounds, which is normal for the depth at which gas is found. On January 1, 1932, the average rock pressure for the field

was approximately 700 pounds and the estimated total open flow from the 29 gas wells was 676,934,000 cubic feet of gas per day.

There are 3,800 acres of proved and semi-proved gas lands in the Sayre field. Assuming an average reservoir thickness of 40 feet, an average porosity of 18 per cent, and that the original rock pressure was 910 pounds, this field originally had 17,657,000 cubic feet of gas per acre, and a total reservoir content of 67,096 million cubic feet of gas at a two-pound base. In addition to the gas withdrawals by utility

TABLE XIII

ANALYSIS OF GAS FROM SAYRE FIELD

	Per Cent
Methane	95.69
Ethane	1.98
Propane	1.03
Isobutane	.34
Normal butane	.41
Pentane, heavier	.55
	100.00

companies and gasoline plants given in Table XII, we estimate that as of January 1, 1932, gas blown into the air while completing wells and gas used for lease purposes amount to 5,800 million cubic feet. It is, therefore, estimated that 17,964,651,000 cubic feet of gas has been withdrawn from the reservoir as of January 1, 1932, or 26.8 per cent of the original calculated reservoir content. The pressure decline from 910 pounds to 700 pounds indicates that 22.7 per cent of the estimated original gas content has been withdrawn from the reservoir. Eight oil wells in the Sayre field produced a total of 344,000 barrels of oil, but most of them are abandoned.

The following companies purchase gas in the Sayre field: Central States Light and Power Company, Consolidated Gas Service Company, and the Westoak Gasoline and Carbon Company. The first carbon plant was completed in December, 1930. This plant consumed 2,440,678,000 cubic feet of gas in 1931. Gas consumed in the manufacture of carbon black is included in the production figures of 1931 as shown in Table XII. There is only one gasoline plant in the field. It has a rated capacity of 13.5 million cubic feet per day.

The B.T.U. content of the gas is 1,105. Gasoline content is approximately $\frac{1}{4}$ gallon per 1,000 cubic feet.

The producing zone appears to have a definite water level around the outer edge of the producing area.

The first wells in the field were drilled with cable tools. Subsequently wells were drilled and completed with rotary equipment,

or standardized when the top of the "Big lime" was encountered and then completed with cable tools. Drilling depths range from 2,600 to 3,000 feet.

Gas pipe lines withdraw gas ratably from all connected wells.

The cost of drilling and completing a well ranges from $20,000 to $25,000. The field is not fully developed but the producing limits are well defined. The wells are spaced one to 40 acres. Wherever lease ownership permits, it is probable that future development will increase the amount of acreage per well.

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RÔLE OF DIASTROPHISM IN TOPOGRAPHY OF CORPUS CHRISTI AREA, SOUTH TEXAS[1]

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ABSTRACT

Corpus Christi is at the center of an area of 35 by 45 miles covered by detailed topographic maps with scale of 1 to 62,500 and 5-foot contours. This area is studied in detail and illustrations from a group of similar maps in Kenedy and Cameron counties, on the south, are chosen. The topographic features are described, with physiographic origins and history. Wells drilled on "unusual topography," or in "broken country," or on surface mounds, without regard to physiographic origins, will continue to produce a high percentage of failures here.

Only one topographic feature of local diastrophic origin is found—a fault scarp or fault-line scarp bounding present development and subsurface diastrophic structures (as now known) in two oil and gas fields. This lies east of the White Point producing area and divides the Saxet producing area into two parts. Some gas has been found across this supposed fault in each field, but with no records of steady production. Dry holes have been drilled on the scarp not far from producing wells in the Saxet field. Oil wells also occur on it. The subsurface relations of the fault have not yet (June 15, 1933) been studied, but cores showing a fault plane are reported (see description of Figure 15).

This fault offsets the upland (Beaumont) deltaic plain and two terraces of Nueces River by 15 feet, vertically, producing a disturbance of gradients in the valley for 7 miles upstream. A distributary of ancient Nueces River turned at right angles to its former course on meeting the White Point structural uplift and continued along the bearing of the supposed fault for 8 miles away from the present entrenched valley to Taft.

The positions of flank dips on the structural noses at the White Point and Saxet fields, as postulated from somewhat inconclusive subsurface data, are coincident with topographic slopes of diverse origins, revealing an alignment believed to represent partial diastrophic control of topography in the immediate areas of the fields but lack of control at short distances away from them. Thus, meander scars associated with flank dips are continued into areas where they can not be expected to coincide with buried structures.

The general topographic features of the area are described from the physiographic viewpoint. Some of these, of non-diastrophic origin, have been thought by some to indicate diastrophic structures and oil occurrence. These include round bays, distributary ridges, segments of a ridge of windblown sand (mature offshore bar) and intrameander mounds. The occurrence of oyster, clam, and snail shells of marine types on high bluffs on the ground surface and in soil is of general, not local, distribution along tidewater bluffs, both high and low, and is solely of Indian origin. Asphalt on gulf beaches either floats ashore from oil seepages in the gulf, from oil waste of ships, as asphalt eroded from South American asphalt lakes, or in barrels from lost cargo and is of general distribution along the offshore-bar beach. Sharp contact of fresh and salty waters in shallow sands along the west side of the mature offshore bar for 100 miles along the coast is not due to faulting, but to accumulation of rain-water in the dune-sand ridges

[1] Presented before the Association at the Houston Meeting, March 24, 1933. The conclusions of this paper supplant those of the paper on the physiography of this area at the New Orleans meeting of the Association, March, 1930 (Price, 1930a).

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and its downward and outward penetration into underlying sediments to depths of 100 feet and the resulting contact with the normal saline waters of the area. Large playa basins in the South Texas sand plain south of the area, with associated mounds of clay-dune origin, are wind-scooped and wind-deposited features. The saline ground waters have accumulated by evaporation of in-flowing surface run-off from higher prairie areas and by salt blown inland with silt from coastal flats and with fogs.

Negative evidence from physiography is not considered adequate to condemn any locality in the area as an oil and gas prospect, because we do not yet know the diastrophic history of the area, including the dates of the last deformation at different points. The occurrence of concentric or extensive linear alignment of slopes on topographic features of diverse origins is considered to be strongly suggestive of diastrophic deformation in the subsurface, with reflected surface expression. An example of fresh fault scarps a short distance west of the area shows that other parts of South Texas may hold other such evident topographic effects of diastrophic disturbances.

INTRODUCTION

"Moundology" has had a great appeal in the Gulf Coast to the operator who has not used geology, and to some geologists, including most of them at one or another stage of the study of the coastal areas. Mounds, or any sort of elevation above the generally flat, featureless coastal prairies, have been interpreted as indications of salt domes or of other diastrophic structures favorable for oil and gas accumulation and production.

"Broken country," in contrast to a normally less irregular topography, is a concept which has also for many years had its appeal to some operators who do not use geology. In the flat coastal belt of Texas only a very small amount of topographic relief is required to give "broken country." Thus, many operators have been led to drill wildcat wells and wells planned as extensions of fields because of what was, to them, unusual topography. This condition is operative today and is still leading to financial loss and delay in the development of the coastal area of South Texas.

The Corpus Christi area, comprising a slightly dissected plain of soft clays and sands, with the inland water bodies which mark its seaward edge, is an area in which marker beds for mapping surface geology are almost wholly lacking. This condition persists across the broad outcrop of the Beaumont clay formation until its inner contact is reached. This area does not contain abundant gas seepages. Those which are present seem not to be made conspicuous, as is commonly the case farther north, by a development of that gummy soil condition known as "paraffine earth."[3]

It is not strange, then, that many well locations have been chosen, in the Corpus Christi area, because of a local development of topog-

[3] It is probable that the degree of aridity of the Corpus Christi area is not favorable to the development of paraffine earth, which may require more soil moisture than is present in the dry half of the sub-humid zone (Thornthwaite, 1931).

raphy unusual to the experience of the operator, no careful analysis of the type or origin of the topography and its physiographic history having first been made by his staff.

Since the writer has made an intensive physiographic study of this area, the results of which have not yet been published, and since few petroleum geologists have the opportunity to study physiography in the thoroughgoing manner required to secure satisfactory results in the relatively featureless Coast Prairie of Texas, it has seemed worth while to offer an abbreviated listing and description of those physiographic features of this area which either have figured in the choice of well locations or may be likely to do so.

No attempt is here made to present a full description of all topographic and physiographic features. It is presumed that the student of physiography will readily recognize from the maps listed the commoner features omitted from the descriptions, and that they will not concern the petroleum geologist.

Rôle of diastrophism in topography.—The regional subsurface stratigraphy and structure are too little known and too few oil and gas fields have been developed and studied in detail in the subsurface, to permit a theoretical prediction from known facts of the amount of topographic expression to be expected in the area. Only the diastrophic movements of Pleistocene and Recent age seem to have affected the surficial deposits. There is current evidence that diastrophism is continuing in Texas to-day, since several earthquakes and ground movements have lately been recorded (Bryan, 1933; Sellards, 1933). The fresh fault scarps of the Laura Thompson topographic graben, just west of the Corpus Christi area, show that the topographic evidences of late diastrophic movements may be well preserved in some places (Fig. 1).

What, if any, indirect expression of an ancient, completely buried topography may be found at the present surface is not considered.

If the area has had the same general diastrophic history as the Houston area, we would expect that some oil-bearing areas would be overlain by strata which show no deformation.

At the end of the paper are discussed a series of physiographic and topographic features which seem to show the existence of a fault in the area of the Saxet-White Point oil and gas fields. While the evidence so far gathered on this supposed fault is largely circumstantial, the writer feels that it is highly suggestive.

After presenting the general physiographic features of the area, without attempting in this place a full treatise on the physiography—although some new types and newly described history are included—

(Photographed from the air and copyrighted by Edgar Tobin Aerial Surveys.)

FIG. 1.—Laura Thompson topographic graben. Reproduced by courtesy of Edgar Tobin Aerial Surveys from their 14 S., 20 E., grid square. Medio Creek, at north, and Aransas River, at south, with transverse "valley" between fault scarps. "Valley" is topographic graben between opposing low scarps and probably represents structural graben. Latitude and longitude lines are 28° 18′ 43″ N. Lat. and 97° 33′ 45″ W. Long. Area is in Bee County, Texas, between Blanconia on the northeast and Papalote on the southwest, near Refugio County line. Scale: 1 inch = 6,000 feet.

lists of topographic features are presented which have in the past influenced the choice of well locations in this area, or may do so in the future. The first group includes features such as round bays, high bluffs, and saline playas, which most commonly intrigue the newcomer to the area before he has seen it and its physiography as a whole. These are thought to be normal topographic features of nondiastrophic origin.

The second group includes the associated features involved in the concept of a fault line or faulted zone crossing the Nueces River Valley between the two producing fields of White Point and Saxet and continuing several miles northeastward. Some apology needs to be offered for not including a subsurface structural study of the fields in support of the suggested topographic expression of "structure." This paper was prepared, however, before the drilling made this possible.[4]

A last-minute study of the structure before publication is not attempted in view of the expectation that these fields will receive fuller treatment in the Association's projected volume, *Geology of Natural Gas*. Perhaps a more unbiased interpretation of the physiographic evidence for the fault may be obtained by completion of this study before a subsurface check is attempted.

In the summary paragraphs, some thoughts as to the assistance of physiography in oil finding in this district are offered. The Laura Thompson topographic graben shows that much more specific topographic evidences of diastrophic structures may be found in places in South Texas than those exhibited on the six topographic maps which form the main basis of this study.

Area and maps.—Six 15-minute topographic maps cover an area approximately 46.5 miles east and west and 34.5 miles north and south between 97° and 97°45′ West Longitude and 27°30′ and 28° North Latitude. These are printed on a scale of 1 to 62,500 or 5,208 feet per inch. Five of these, Aransas Pass, Corpus Christi, Petronilla, Robstown, and Oso Creek, have 5-foot contours and are United States Geological Survey maps. The sixth, Crane Island, covers chiefly water areas, with soundings from the Coast and Geodetic Survey's 1881 data and exhibits the sand-dune topography of Padre Island by stipple. The topographic sheets cover nearly all of Nueces County and parts of Aransas, Kleberg, and San Patricio counties. The soils of the area have been mapped by the United States Bureau of Soils on the Reconnaissance Soil Survey, South Texas Sheet (Coffey *et al.*, 1912a), on the scale of 1 inch to 6 miles and on the Corpus Christi Sheet (Mangum and Westover, 1909), on the scale of 1 inch to 1 mile.

[4] March 20, 1933.

These soil maps show many physiographic features, but not as fully as the soil maps of more recent surveys of Gulf Coast areas.

Topography of the surrounding areas is shown on a generalized basis by Tactical Maps of the Corps of Engineers, United States Army; scale 1 to 125,000, or 1 inch to 10,416 feet. The Corpus Christi sheet of this survey, made in 1908–1909, shows the original shore lines of St. Joseph Island (a young offshore bar) before they were modified by the high water accompanying the hurricane of 1919.

Soundings in bays, lagoons, and the Gulf of Mexico are shown on the several charts of the Coast and Geodetic Survey, the only changes since the 1881 survey being along the Corpus Christi ship channel and other boat channels. Corpus Christi is located at the center of this area.

The area covered by detailed topographic maps of the United States Geological Survey is that referred to here as the Corpus Christi area, to which the present discussion will be largely confined. Interesting topographic features a few miles inland, such as the Alice Terrace of Deussen (1924) and its bounding scarps, and the Laura Thompson topographic graben, so well shown in the aerial photomosaic map 14 south, 20 east, of the Edgar Tobin Aerial Survey's Texas grid (Fig. 1), will not be discussed, since detailed topography of sufficiently extensive areas including these features for physiographic analysis is not available for study. It is possible, however, to follow well marked physiographic and topographic elements of the landscape of the Corpus Christi area into the territory both north and south and to identify there forms similar to those occurring in it, because the strike or trend of the principal units is parallel with the shore line. In this wider study, the reconnaissance soil maps noted, and that of the central Texas coast (Coffey *et al.*, 1912b), are an aid. Other topographic maps of South Texas coastal areas, namely, the group in Kenedy County and those of the Lower Rio Grande Valley, are useful in this connection.

ACKNOWLEDGMENTS

More complete references to sources of information and citations of similar cases described by others, with full lists of those individuals contributing assistance in the writer's study of the physiography of South Texas, will be presented in a longer manuscript on the subject now in preparation. To Alexander Deussen for his published description of the major topographic features of South Texas, to Douglas W. Johnson for his basic treatise on shore-line physiography, and to C. Wythe Cooke for his recognition of the Corpus Christi area as being

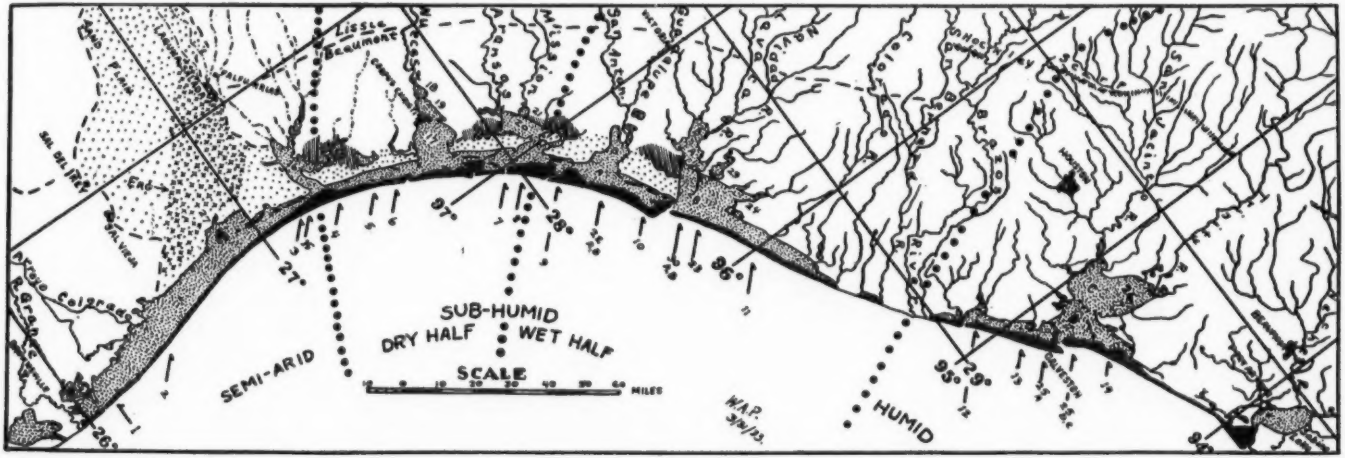


FIG. 2.—Coast Prairie of Texas (Beaumont Terrace) as bounded on west by Lissie-Beaumont contact of Deussen (1924) south of San Bernard River, and on north by Hockley Scarp (Barton 1930b). The portion between Brazos and San Bernard rivers is not accepted by Barton, being mapped by Price. East margin formed by Gulf of Mexico, coastal lagoon and bays (fine stipple), basins of ancient lakes and bays of Ingleside Terrace (lined areas), and by mature offshore bar (dotted). Young offshore bar of Texas coast with spits and islands shown by solid black. Sand plain (dotted) of Kenedy County ("The Desert") crosses Coast Prairie between Sal Vieja and Laguna Salada. Approximate area of Kenedy County dune field (*erg*) shown by small crosses. Thornthwaite's (1931) quantitative classification of climate indicated by zone boundaries (solid circles in lines) which will probably be revised to turn southward on Coast Prairie to follow high-moisture belt. Arrows show positions and numbers of lagoon and bay profiles of Figure 7.

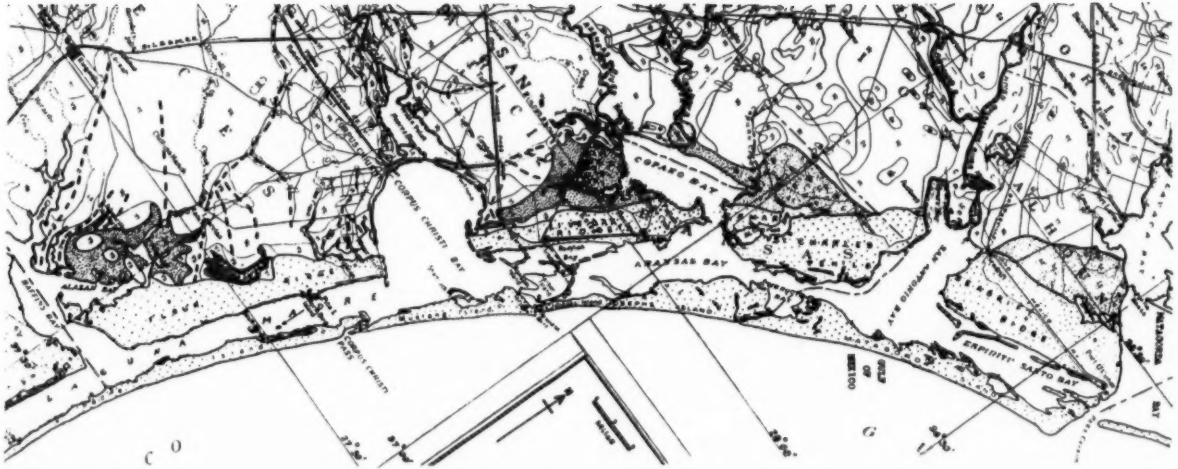


FIG. 3.—Reconnaissance soil map of portion of Coast Prairie. Ingleside Terrace abandoned lakes (or bays) are undrained swampy land marked by Lomalta clay soil (finely stippled). Young (dune sand) and mature (Nueces sand soil) offshore bars are dotted. Distributaries of ancient Nueces and of former tributaries of Baffin Bay are marked by Victoria loam (*Vl*) and fine sandy loam (*Vs*) soils (axes of distributaries shown by dashed lines, partly inferred). Victoria clay soil (*Vc*) covers remaining areas south of Copano Bay. Soil pattern shows other distributaries north of Copano Bay (*Es*, Edna fine sandy loam, and *El*, Edna loam soils). After Coffey *et al.* (1912a and 1912b).

chiefly of deltaic rather than lagoonal origin, the writer is particularly indebted. Barton's clear description of the deltaic coastal plain and Coffey's recognition of clay dunes also furnished basic information. Sellards first pointed out clay dunes as such in this area.

A field trip with Douglas Johnson settled the identification of the mature offshore bar and aided in arriving at a clearer conception of the climatic factor in the distribution of physiographic elements, already then a subject of investigation by the writer. Thanks are due to the Edgar Tobin Aerial Surveys for permission to reproduce photographs of Laguna Salada and the Laura Thompson topographic graben taken from the air by them. Thanks are also due to Donald Barton and Marcus Hanna, who read the manuscript and offered constructive criticism.

GENERAL TOPOGRAPHIC FEATURES OF AREA

Beaumont Deltaic Plain.—With the exception of the river valleys, water areas and low swampy areas along the coast, including tidal flats, bars, spits, and islands, the whole of the Corpus Christi area is on the Pleistocene Beaumont Terrace of Deussen, or Beaumont Deltaic Plain of Barton, which is also called the Coast Prairie (Deussen, 1924, p. 5). This surface slopes gulfward 2.5 feet per mile (Fig. 2).

Deltaic coastal plain.—The topography of the land area of the Beaumont Terrace is that of a deltaic coastal plain, described in detail by Barton for the area northeast of Brazos River (Barton, 1930a; 1930b). It is characterized by broad, low, irregularly hummocky and winding ridges of sandy soils which mark the courses of ancient rivers which ran on the surface of the upland before the period of entrenchment which produced the present canyons of the master streams of South Texas and the V-shaped arroyos of some short branches (Fig. 16).

Distributary ridges form the chief variations of the surface of the Beaumont Terrace. They represent aggradational deposits of the coastal ends of non-intrenched streams. They are as much as 15–20 feet high, though commonly caught by only one 5-foot contour, and as much as 4 miles wide. The natural levees which formerly bordered the ridges at their summits have been weathered down, the ridges now having a broadly convex profile. On soil maps the distributaries are marked by lines and tongues of sandy soils within areas of less sandy soils (Fig. 3). Victoria loam or Victoria fine sandy loam marks most distributaries south of Mission River. Edna fine sandy loam marks them thence northward to Colorado River (Coffey *et al.*, 1912a; 1912b; Mangum and Westover, 1909).

Some streams of South Texas have become entrenched close to their old distributaries, or actually in them, as in the case of Nueces River in this area (Figs. 15 and 16). Consequent streams flow on, or are entrenched in, the flats between distributaries, their drainage basins being bounded by these ridges commonly to the edge of the Beaumont Terrace. Gulfward ends of the distributaries are, in general, the parts best preserved. Distributaries branch gulfward at high angles, the junction of the ridges in places not being preserved.

Delta-front slopes.—The uniform slope of the Beaumont Terrace is broken in places, observed chiefly near its gulfward edge, by very low, irregular scarps with scalloped outline. These represent initial slopes on the fronts of areas of deltaic deposition formed probably under water and some have been cliffed by marine planation (Fig. 4). The cusps of their scalloped outlines represent recessed curves between projecting distributary ridges, some of which are of very slight development.

Upland sand dunes and playas.—Almost the only other natural topographic features of the upland (Beaumont Terrace) are widely scattered, low, isolated sand dunes, with their shapes modified by cultivation, and shallow playas without cliffed margins, now mostly drained and marked only by areas of poor (acid?) soil. These hold water for a short time after heavy rains (Fig. 16).

Artificial earth structures of upland.—Long lines of sharp-ridged spoil banks of drainage ditches, of triangular cross section, 5–10 feet in height, usually having gaps at short intervals, interrupt the view across the prairie in some areas. They resemble long lines of box-cars or elongated tents in precise rows.

Water for farm and ranch use is commonly stored in earthen reservoirs called *tanks* or *tanques*. These may be circular with enclosing walls of earth, 5–10 feet high, or quadrangular with spoil banks piled at the sides, accordingly as they were constructed with scrapers or ditching machines of the dredge type. A few irrigation ditches, in the Robstown area, are elevated above the prairie with low earthen walls.

In the White Point and Saxet oil and gas fields are earthen craters formed by the accidental escape of gas and salt water under pressures varying from 600 to 1,300 pounds per square inch, the flow of some lasting for months. These are as much as 1,000 feet in diameter, at the top, 50 feet deep, and are surrounded by earthen walls as much as 15 feet high (Fig. 15).

Stream valleys.—The master streams of South Texas, such as Nueces River, have broad flood plains and steep, canyon-like walls.

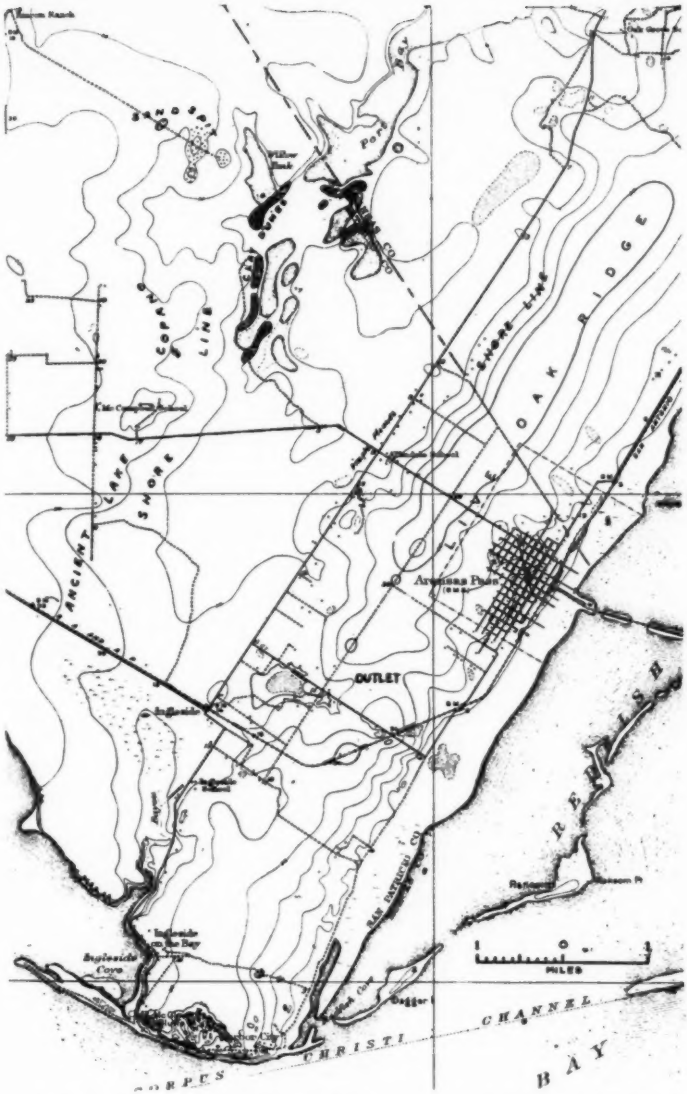


FIG. 4.—South end of abandoned Lake Copano, an Ingleside Terrace basin, with part of mature offshore bar, Live Oak Ridge. Aransas Pass Quadrangle; 5-foot contours. High level of ancient lake marked by sand spit west of Willow Tank and former outlet from lake to Gulf of Mexico located between Ingleside and town of Aransas Pass (present tidal inlet of this name is 7 miles southeast). Shore-line scarp of Lake Copano caught by 10-, 15-, and 20-foot contours. Port Bay, arm of present Copano Bay, is entrenched in lower part of old lake basin to present sea-level. Recent silting of Port Bay shown by swamp with ponds and clay dunes. Willow Tank is dammed in part by clay dune. Valley of Kinney Bayou forms recent gap in old lake shore. Scalloped contours along west shore of old lake mark terminal ends of distributary lobes of ancient Nueces delta. Subdued, forested sand dunes of Live Oak Ridge contrast with active sand dunes of Corpus Christi Bay shore at end of ridge (McGloin Bluff winged headland). East spit of this headland is aligned with bay bars which separate Redfish and Corpus Christi bays.

The Nueces, being a river of the dry portion of the sub-humid zone (Thornthwaite, 1931), near the semi-arid zone, has, throughout its course, relatively few branches,[5] and none in the Corpus Christi area except short, valley-wall drains, only one of which, Hondo Creek, has cut across the ancient distributary ridge in which the river is entrenched (Fig. 16). This ridge was once more than 9 miles wide and seems to represent a raised deltaic zone, or a pair of distributaries rather than a single one.

This old distributary, or the natural levees of ancient Nueces River, if we prefer so to think of them, throws the surface drainage away from the river, forming divide ridges asymmetrically placed at the edge of the canyon walls.

Creeks such as Oso Creek, with many others along the coast which head in the Beaumont Terrace, are continued headward, in some places for 2 or 3 miles, by broad, low swales which show no erosion of the sod (Fig. 15).

Flood-plain bars of sand; projections of the canyon walls left behind meanders and known as *intermeander spurs;* river terraces and other typical flood-plain features are found here (Figs. 15 and 16). Terraces of Nueces River will be discussed as indicators of faulting (Figs. 16 and 17).

Drowned, embayed stream mouths.—All streams of the area, and of the coast of South Texas, except very recent bluff drains, and the deltaic Rio Grande, end in tidal estuaries (Figs. 2, 3, 8, 11, 15, 16). These, in the case of the smaller inter-distributary consequents, as the "Cayo del Oso" (properly, *La Cala del Oso*), the winding estuary of Oso Creek, are commonly funnel-shaped (Fig. 8). The larger subsequents of the deltaic Beaumont Terrace now end in broad bays.

Entrenched meanders of small, weak consequent streams, such as Oso Creek and the unmapped Mud Flats estuary emptying from the southwest at the mouth of Aransas River (Fig. 3), indicate entrenchment at a relatively late date. The entrenched walls of these creeks rise 10–20 feet above sea-level.

Live Oak mature offshore bar.—A broad sand ridge stands on Beaumont clay at 5–8 feet above sea along the mainland shore of the coastal lagoon (as Laguna Madre, Red Fish Bay, Aransas Bay, Figures 2–4, 8). This ridge ranges from 3 to 8 miles in width and has been mapped with a height of 22 feet (elevation of top, 30 feet) west of Aransas Pass. The ridge is interrupted by Corpus Christi, Copano,

[5] That is, *in-flowing* branches, a feature characteristic of master rivers of a deltaic plain (Barton, 1930a, b), which, in the case of Nueces River, is emphasized by its arid environment. The Nueces has fewer branches in its lower reaches than the Brazos or Colorado.

St. Charles, and San Antonio bays, so that it forms 5 fragments, having an over-all length of 100 miles. The ends of these fragments project into the bays as short, blunt peninsulas from the ends of which spits extend into the water like extended fins or wings.

The ridge, or mature offshore bar, is composed of dune sand. The dunes have subdued slopes, being fixed by vegetation except on the immediate shores of large bays whose winds have formed active dunes stopped inland by protective vegetation.

This line of ridges (Deussen, 1924) consists of the ridge south of Flour Bluff Point, which is here called *Flour Ridge*, Live Oak Ridge and the sand-ridge portion of Live Oak and Lamar peninsulas, St. Charles Peninsula, and a segment between Seadrift and Port O'Connor which seems not to have been named and which is here called *Seadrift Ridge*. The entire bar will be referred to as *Live Oak mature offshore bar*.

The conclusion that the remnants of this offshore bar now rest on the mainland of the time of its retreat to the shore line was reached by Douglas W. Johnson and applies definitely only to those segments visited by him and the writer, namely, Flour Ridge and Live Oak Ridge. The slope of the Beaumont Deltaic Plain is such that it would have coincided with the clay contact under the mature bar sands if extended across the basins of present bays and of the Ingleside Terrace basins shortly to be described. Moreover, lagoonal materials and shells or shell fragments were nowhere found along the sand-clay contact where this was examined. The clay under the sand is like that of the Beaumont of the adjacent areas.

Ingleside Terrace (*Recent Terrace of Deussen, in part*).—The coastal edge of the Beaumont Deltaic Plain (Beaumont Terrace of Deussen) ranges in elevation, in this area, from 8 to 35 feet. This plain terminates seaward in the bluffs of the present bays (Fig. 17) and of the coastal lagoon (including localities where the Live Oak mature offshore bar overlies it) and in low, modified ancient bluffs which face swampy, undrained lowlands immediately interior to the several segments of the Live Oak mature offshore bar, shortly to be described.

These swampy flats are here designated as the Ingleside Terrace. They, with the other coastal flats, islands, bars, and spits, all apparently of Recent age, were defined by Deussen as the Recent Terrace or Plain. The Ingleside Terrace consists of extensive flats, now isolated by intervening bodies of water and by areas which are apparently of deltaic origin and are not swampy, which flats appear to have been the sites of a series of lakes or lagoon segments when the mature offshore bar reached the mainland shore and dammed the lesser streams

behind it. This lagoon, or series of lakes, was apparently of fresh water, if the interpretation offered is correct.

The Ingleside Terrace basins, therefore, are enclosed between low shore bluffs along their inland sides and segments of a formerly continuous sand ridge or bar on their seaward sides, except where bays and streams have since destroyed these former shore-line features.

Five large remnants of the Ingleside Terrace have been recognized in South Texas. They lie between Matagorda and Baffin bays and are coincident with those areas mapped as Lomalta soils on the reconnaissance soil maps of the coast (Coffey *et al.*, 1912a; 1912b) lying between the bays mentioned and not including Lomalta clay on river flood plains and sand spits. The locations of these remnants are as follows (Fig. 3).

1. Calhoun County, between Seadrift, Powderhorn Bayou, Magnolia Beach, and the mouth of Chocolate Creek, interior to Seadrift Ridge.
2. Aransas and Refugio counties, along the west shore of Copano Bay northeast of Mission Bay and in the triangular part of Aransas County north and west of St. Charles Bay, but west of a portion of Lamar Peninsula between lower St. Charles Bay and the mouth of Copano Bay.
3. Aransas and San Patricio counties, south of Copano Bay, surrounding Port (Puerto) Bay and extending in a narrow tongue from the south end of Port Bay to Ingleside within a fraction of a mile of Corpus Christi Bay (Fig. 4), interior to Live Oak Ridge.
4. The basin of Laguna Larga, Nueces and Kleberg counties, interior to Flour Ridge.
5. Kleberg County, west of lower Alazan Bay and surrounding its upper estuarine branches to the mouth of Agua Dulce Creek; east of Jaboncillos Ranch headquarters of the soil sheet, interior to Flour Ridge and Alazan Bay.

The bluffs which margin these basins along their western sides are caught by the 10- and 20-, or 25-foot contours of the Aransas Pass and Oso Creek sheets. The bluffs are slightly gullied, only a part of the erosion being shown on the maps. The original shore-line bluffs along the eastern side have probably not held their shape in the loose dune sand, but steepening of the west slope of the mature offshore bar shown in places on the topographic maps may be the result of former wave action on the old bodies of water of the Ingleside Terrace.

The lower portions of the present basins of the Ingleside Terrace are occupied by bays, with the exception of the Laguna Larga playa. These bays are margined by low bluffs, in most places, which lie below the swampy plain of the ancient lagoon. In other places, the old lagoon bottom slopes more or less imperceptibly to marshy shores of the present bays. Laguna Larga playa has no outlet and is a modern intermittent lake occupying a basin which seems to have suffered little change since the other Ingleside Terrace basins were abandoned.

The floor of the Laguna Larga basin lies between the 10- and 15-

foot contours. That of the basin south of Copano Bay has the same elevation. Features helping to fix the position of the ancient basin floor and shore bluffs include the ancient sand spit 0.75 mile west of Willow Tank and 1.5 miles west of the southern end of Port Bay. Its foot is defined by the 10- and 15-foot contours (Fig. 4). A former outlet of this basin through the mature offshore bar is shown 1.5 miles southwest of the village of Aransas Pass. This outlet is caught by the 15-, 20-, and 25-foot contours. A depression lying below the 10-foot contour is located along the axis of this depression just north of the town of Ingleside. The outlet may formerly have been floored at or below an elevation of 10 feet above present sea-level and the old channel have since become partly filled by the dune sand. This former outlet is in the nature of a so-called "wind gap" left by stream piracy.

Distributary ridges of the ancient rivers extend into the west sides of the Ingleside Terrace basins, producing a scalloped outline for their ancient shore lines. The bases of these distributaries are caught by the 10-foot contour on the maps cited.

The upper end of Port Bay has partly silted up below the shore of the old Ingleside Terrace basin. Ponds and swamps mark the former extent of Port Bay; clay dunes have been formed on the west sides of these ponds and swamps which are either saline or subject to occasional overflow by bay waters. Clay dunes form natural dams for some ponds here.

The several basins of the Ingleside Terrace are here termed lakes and designated as Lake Matagorda, for the Calhoun County remnant; Lake Copano, for the old basin partly surrounding Copano Bay; and Lake Baffin for the ancient basin which once included Laguna Larga and which is now entrenched by Alazan Bay, an arm of Baffin Bay.

The town of Ingleside is situated in the extreme southern neck of Lake Copano where the Nueces delta shut it off from communication with the gulf and with Lake Baffin at this point (Fig. 4). The recent ravine of Kinney Bayou has become extended headward to tap the swamp in the neck of Lake Copano at Ingleside. The Humble Oil and Refining Company's refinery stands in the old lake basin at this point. The village and refinery constitute the only economic development of the Ingleside Terrace aside from some recent attempts at cultivation of the poorly drained flat. The greater part of the terrace is grazing land to-day.

This terrace may be correlated in age with the Pensacola Terrace of Leverett (1931) or with one of its subdivisions (Cooke, 1930a, b, 1931). This broad terrace of the coastal plain of Florida is similar in position and general features to the Ingleside Terrace.

"*Pimple Mounds.*"—These features (Veatch, 1906, pp. 55–59; Deussen, 1924, pp. 6–7; Melton, 1929), common on the coast prairie north of Brazos River, where they are associated with distributary ridges and other sandy soils, have been noted south of Copano Bay, only along the landward bases of the young and mature offshore bars (Fig. 4), where they show no up-flow structure assignable to gas or water seepage and are said by Clyde T. Reed[6] to be definitely associated here with the establishment of vegetation on a bare surface of loose sand and with the consequent growth of succeeding floras as the climax vegetative formation is reached for this environment, struggling constantly against loss of soil by erosion.

Distributary ridges of ancient Nueces River.—The most prominent distributary ridges of Nueces River are those which parallel its valley at the top of the canyon walls. Their width ranges from 1 mile to 3 miles and their height from 5 to 10 feet (Figs. 15, 16). They are marked on soil maps by sand and sandy loam soils which, in many places, show a slight development of the vertical jointing typical of loess. The material is too coarse-grained and impure to be a true loess, but suggests in its structure a content of windblown silt.

These distributaries may be parts of a single broad deltaic ridge. From it branch several more or less well preserved distributaries (Fig. 3), of which the most prominent is that which is shown 6 miles south of the valley at the west edge of the Robstown Quadrangle sheet and which crosses the Texas Mexican R. R. and the St. L. B. & M. R. R. 2 miles southwest of Robstown, Nueces County. This ridge is 33 miles long; is continuously marked by sandy soils; ranges from 1 mile to 3 miles in width, and is caught by one or two 5-foot contours, except at its branching end along the shores of Laguna Madre and Mujeres Playa (east of "Majiris"—properly, *Mujeres*—Tank) where it catches three contours. Its branches end at the shores of Ingleside Terrace basins, with the exception of the axial branch, which joins the mature offshore bar, Flour Ridge segment, south of Laguna Larga.

Another branching distributary, less well shown on the topographic maps, crosses the St. L. B. & M. R. R. between Driscoll and Bishop south of Agua Dulce (Petronilla) Creek and also extends to the shores of Ingleside Terrace basins. One of these branches probably reached Baffin Bay at "Sandy Point" between Grullo Bayou ("Cayo" del Grullo) and Alazan Bay.

Remnants of distributary ridges can be distinguished in the topography and soil patterns on both sides of Oso Creek (Fig. 8). North

[6] Professor of biology, College of Industrial Arts and Industries, Kingsville, Texas.

of Nueces River, distributary ridges branch northward from near the West Portland Gin, 4 miles northeast of White Point; one going 2.5 miles west of the town of Taft, and one passing through it. Other distributary branches flowed eastwardly and northeastwardly past the town of Gregory and formed the scalloped west shore line of Lake Copano (Fig. 4), the ancient basin of Ingleside Terrace west of

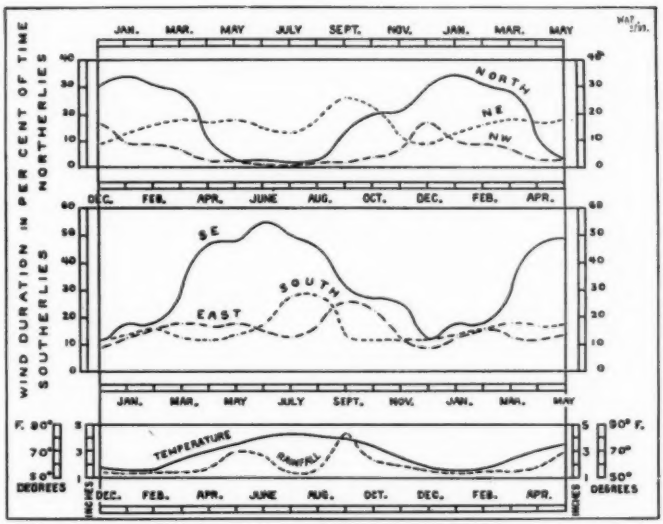


FIG. 5.—Seasonal distribution of climate at Corpus Christi, Texas, from United States Weather Bureau data. Rainfall and temperature curves show average monthly values for 43 years of record, 1887–1929. Wind duration curves show average values for 9 years of record, 1923–31, inclusive. Monsoonal character of winds shown by alternating relation of peaks of two stronger winds, southeast and north. Association of temperature peak, two rainfall peaks, and peaks of southerly winds explains origin of clay dunes exclusively under the southerly winds (as here designated).

Aransas Pass. One of these flowed 12 miles northeast from Gregory past the Rincon Ranch headquarters, in the northwest corner of the Aransas Pass Quadrangle, and continued northward to where it is now abruptly truncated by the shore line of Copano Bay. The northern end is beautifully preserved and is shown by a sinuous tongue of Victoria fine sandy loam on the soil sheet (Coffey, 1912a). The Mud Flats tidal estuary lies along its west slope and empties into Copano Bay at the mouth of Aransas River. This estuary has not been shown on Government maps (Fig. 3).

The spread of the ancient Nueces distributaries here described occupies a front of 58 miles of the west shore line of the Ingleside Terrace (Fig. 3). A few branches crossed this terrace and mark outlets of the river into the Gulf of Mexico prior to the formation of the present (young) offshore bar. One of these has been described; one or more are believed to have been destroyed by Corpus Christi Bay.

These distributaries control the present drainage of consequent streams, the positions of estuaries, and of Ingleside Terrace basins, both at its ancient high shore line and at the low shore lines of the bays now entrenched to the present sea-level.

Physiography of water areas.—The writer has given considerable study to this problem in South Texas, but can merely summarize the results in this place. The southeast wind is far stronger than any other (Fig. 9) and dominates for 10 months of the year, including the hot months (Fig. 5). This wind, and its waves, have produced many visible effects in South Texas, including deep indentation of the coast.

Some bays of South Texas began as drowned river valleys (Baffin, Corpus Christi, Nueces, Mission, Hines, San Antonio, Lavaca), now silted to shallow depths; others (Alazan, Copano, Matagorda) began as basins of the Ingleside Terrace, later trenched by streams during a recession of sea-level. Widening of these bays by waves then occurred on a large scale. Some bays have their processes so adjusted between sedimentation and erosion that they are sub-circular in outline (Corpus Christi, Mesquite, Mission). An excellent example of extensive marine planation in bays is to be found in the fragmentary nature of the drainage basin of Taylor Bayou and adjacent streams along the shore of the inner half of Galveston Bay between Seabrook and Laporte (see topographic sheets and Harris County soil map).

The bays have cut into the Ingleside Terrace. Matagorda Bay has destroyed the north half of Lake Matagorda basin (Fig. 2). Copano Bay with its arms has been enlarged in and entrenched below the old Lake Copano. St. Charles Bay has tapped the north end of Lake Copano basin. Corpus Christi Bay has very nearly tapped the south end. Lake Baffin probably once had a northern outlet through Laguna Larga and the area now occupied by Corpus Christi Bay. Alazan Bay, an arm of Baffin Bay, has cut into the east side of Lake Baffin.

The present bays have been scoured down to 8–15 feet below present sea-level, or 23–30 feet below that of the Ingleside Terrace. The fresh bluffs of the bays are in sharp contrast with the subdued bluffs of old basins of Ingleside Terrace,[1] long since smoothed by erosion (Fig. 4). A young offshore bar now encloses a salt-water coastal lagoon

(Figs. 2–4) which contains, in some areas, many islands, bars, and spits (Figs. 4, 14).

Origin of mature offshore bar and Ingleside Terrace.—The topography of the shore areas is sufficiently complete to permit a fairly reasonable attempt to outline the past physiographic history of the coast since the end of deltaic deposition of Nueces River upon the Beaumont Deltaic Plain. This history is sketched here, the writer reserving a full discussion of the problems involved for treatment elsewhere.

The mature offshore bar is believed once to have occupied a position offshore similar to that of the present young offshore bar of Padre Island and its extensions north and south. This position may have been near that of the present young bar (Figs. 2 and 3). This bar extended at least 100 miles along the coast from Baffin Bay to the edge of the Colorado-Brazos delta. It was probably much longer and similar in distribution to the young offshore bar of to-day.

The attack of the waves drove the bar to shore (Fig. 6A) along most or all of its length, but the opposing action of river deltas probably prevented its coming to rest permanently on the Colorado-Brazos and Rio Grande deltas except perhaps along their margins. Along the front of these deltas to-day the present young bar is tied to shore and is intermittently preserved or marked by a narrow sand ridge. Where the mature bar has been examined by the writer, it seems to overlie the mainland (Beaumont Deltaic Plain) of the time of its retreat to shore, because of the lack of shell material along its contact with the underlying Beaumont and because of the identity of the lithology of the underlying clay with that of the adjacent Beaumont clay of the inland areas. In particular, the caliche development—including columnar nodules several inches in diameter and a red and green mottling of the clay—of the clay under the bar and of the mainland Beaumont is identical.

Although the shore line has suffered oscillations of sea-level since the formation of the mature bar and the Ingleside Terrace basins, including relative uplift of the land, it is not thought that the preserved portions of the mature bar rose from positions in the Gulf, but that the bar had already retreated to land, along these sections of the coast, and its sands had been blown on the edge of the upland over a low bluff. Barton points out[7] that the sand bar could have retreated to a coast of gentle slope and low elevation above sea, similar to that of the coast at High Island salt dome, Chambers and Jefferson counties, to-day, where there is only a 1-foot bluff. Johnson, however, de-

[7] Editorial comment.

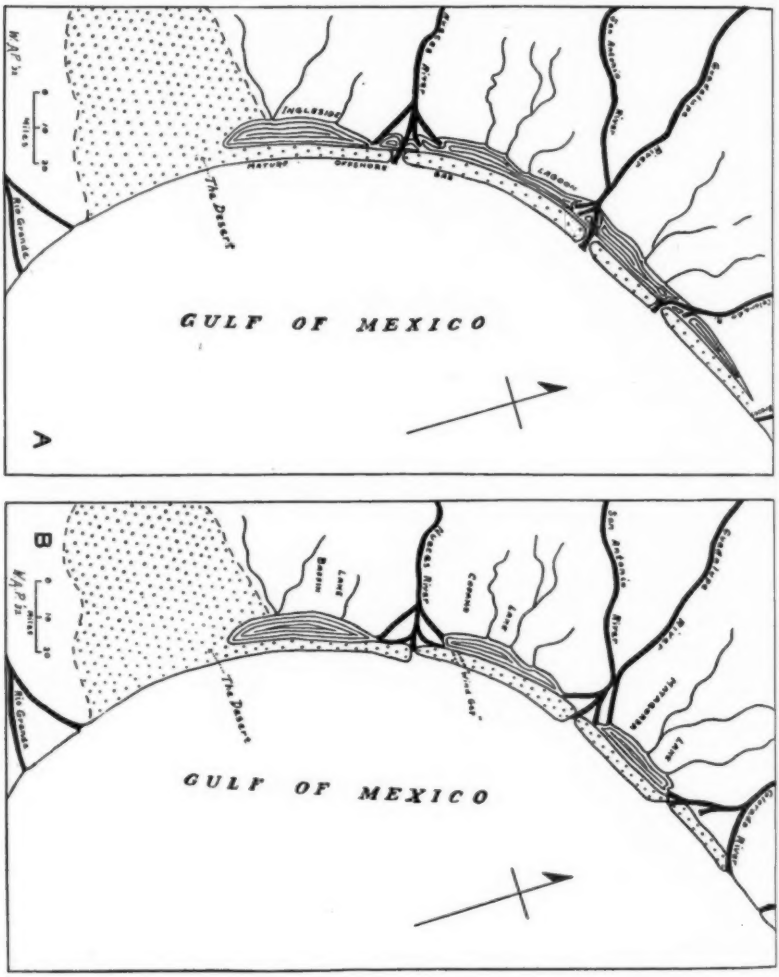


FIG. 6.—Development of Ingleside Terrace and bays, estuaries, bars, and sand plain of South Texas.

A. Offshore bar retreated to shore; master streams flow into gulf but have distributaries which discharge into lagoon or lakes formed by ponding of lesser streams. Sand plain, "The Desert," formed in southern semi-arid area.

B. Deltas of master streams have invaded lakes and are tangent to mature offshore bar. Gaps in this bar will quickly widen. Lakes probably connected with gulf through few narrow outlets, as Ingleside-Aransas Pass "wind gap."

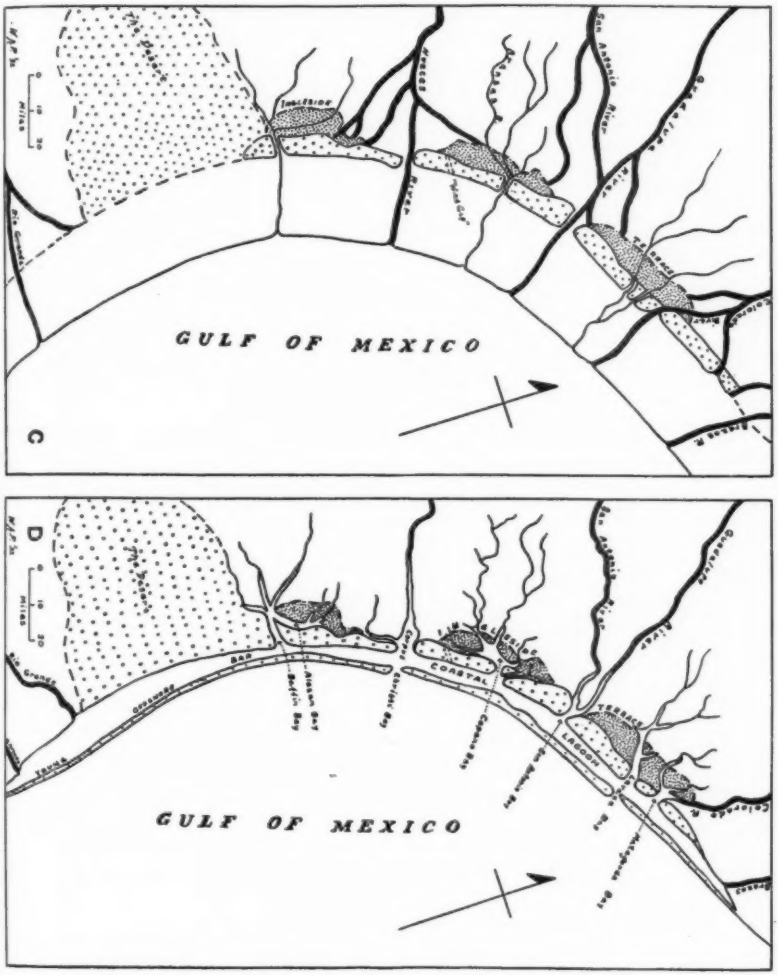


FIG. 6.—*C*. Sea-level falls relative to land; shore line retreats unknown distance seaward along continental shelf. Minor streams and some master streams trench lake beds in canyons 50 to more than 75 feet deep. Little erosion of broad, flat upland stream divides. Terraces of Nueces River indicate shore-line retreat is by 3 or more stages.

D. Sea-level rises to 10 or 15 feet below former position, drowning canyons of Stage *C* and lower terrace of Nueces River. Drowned estuaries are quickly widened into bays by marine planation. Estuaries of master streams develop bays with axes transverse to coast line; those of minor streams empty into longitudinal bays entrenched in Ingleside Terrace basins or develop small bays tributary to longitudinal bays.

scribes cases in which winds lift the sands of a mature bar to the top of a high cliff (1919, Fig. 119-H). If tropical hurricanes were as frequent and as powerful then as now, many long portions of the Texas coast must then have had cliffs somewhat similar in height to those of South Texas to-day. The wind maximum along the South Texas coast has produced higher cliffs there than farther north.

When the sand of the mature bar appeared on the mainland prairie, it became fixed in position by vegetation in the area north of Baffin Bay. This vegetation may have consisted only of grasses and low plants, as the present live-oak and chapparal (mesquite) floras of the bar are of recent origin, during the past 20–40 years.

When this bar reached the mainland and became fixed as a ridge it ponded the lesser streams, but was probably not preserved across the mouths of the master streams, Nueces, San Antonio-Guadalupe, Colorado-Brazos, and Rio Grande, but was tied to the edges of their deltas.

If the foregoing interpretation is correct, there were formed a series of fresh-water lakes or long, narrow lagoons which did not communicate with the gulf. It is quite possible that incidents of river meandering opened outlets for one or more of the lakes during this early period, or that overflow outlets became entrenched to sea-level. Laguna Larga appears to have had an outlet northward into the Oso Creek area. No definite shore-line bluffs are preserved west of the Oso Creek estuary (La Cala del Oso) and the probable movement of dune sand since makes the precise determination of the events uncertain. The Laguna Larga basin may have been closed northward against Flour Ridge by a lobate extension of the Nueces delta, as was Lake Copano against Live Oak Ridge at its southern end.

South of Baffin Bay, in the semi-arid zone (Thornthwaite, 1931), the vegetation must have been insufficient to hold the sand in a coastal ridge, or the coming of aridity there in more recent time has permitted the sand to become widely distributed inland over the area of the sand plain of Kenedy and adjacent counties (Fig. 2). This sand plain has been described by many writers, including Deussen (1924) and Trowbridge (1923 and 1932). It was formed in part by this sand of the mature offshore bar and has since been added to by sand scoured by wind out of a shoaling coastal lagoon.

The Ingleside Terrace lakes and lagoons, if they contained fresh waters and if formed by the ponding of streams, did not form a typical *coastal lagoon* as defined by Johnson (1919), using it in the technical sense, although it was then the only group of large lagoons along the coast of which the writer has found records.

Further discussion of this history is presented in the following outline. It will be observed that the presence of the mature offshore bar of loose sand and of the ancient sand spit in Lake Copano preclude the possibility that the sea has since risen over these areas. If the sea entered the Ingleside Terrace basins to a depth of only a few feet, the mature bar would then have been caused to retreat, to some extent at least, across marine or brackish-water lagoonal deposits, which have not been found beneath it.

Outline of physiographic history of Tidewater region.—This may be briefly summarized as follows.

Event 1. Deltaic distributary ridges extended across Beaumont Deltaic Plain to and beyond present mainland shore line

Event 2. Retreat of offshore bar to mainland, forming:
In sub-humid zone, a. Coastal sand ridge topping shore-line cliff
b. Fresh-water (Ingleside) lagoon and lakes behind it; bottom at 10 feet above sea along its east side
In semi-arid zone c. Sand plain of wide extent (Fig. 6A)

Event 3. Ingleside lagoon cut into separate basins by extension of distributary ridges and deltas across it (Fig. 6B). Resulting basins scoured by waves, in central areas possibly to or below present sea-level. Position of sea-level undetermined but probably below present 10-foot contour. Main channels of master streams cut below water level of Ingleside basins

Event 4. Sea-level fell probably by two movements, shore line retreating seaward beyond present shore line (Fig. 6C). Terraces of Nueces River were cut. The higher terrace seems to have had broader meanders than the present stream. This condition has been pointed out by Barton for Pleistocene streams of the Gulf Coast (Barton, 1930a). It indicates a period of larger run-off than that of to-day, which may have been chiefly due, as Barton thinks, to heavier rainfall. Streams trenched Ingleside Terrace deposits and stream deltas. Some overflow outlets of the Ingleside Terrace basins were left as "wind gaps"; others deepened by streams. Channel of Aransas River cut through present mouth of Copano Bay (lying more than 75 feet below present sea-level). Resulting canyons remained narrow. No other appreciable dissection of upland prairie on Beaumont and recent deposits

Event 5. Sea-level rose to present position, drowning canyons and forming bays in lower parts of Ingleside Terrace basins. Laguna Larga escaped alteration during events 5 and 6, as it had no entering stream. New (young) offshore bar formed (Fig. 6D)

Event 6. Deep canyons filled with sandy silt to level of bay adjustment; bays greatly enlarged (in estuaries of streams of large run-off) by marine planation (lateral wave cutting). Canyons of short and of intermittent streams remained as elongate or funnel-shaped, shallow, tidal estuaries (Baffin Bay). Mature offshore bar widely breached by bays of major streams, but slightly breached by bays and estuaries of streams of small run-off. River valleys widened by lateral (fluvial) planation with development of river terraces

Event 7. Possible recent minor oscillations of sea-level may be required by the occurrence of meander scars along the walls of the river valleys in the present embayed portions.

Event 8. Opposing currents shoal coastal lagoon, more sand blown on shore into "Desert," forming Kenedy County dune field (*erg*) of ridge-type sand dunes trending N. 45° W. parallel with dominant on-shore drying wind

Minor features of water areas.—All the observable irregularities of the coastal lagoon and bays, consisting of low flats, beaches, bars,

inlets, coves, islands, and spits are of wave and current origin, with the exception of reefs of organic and chemical origin. Full descriptions of these physiographic units and of their origins may be found in Johnson's treatise on shore-line physiography (Johnson, 1919). Small reefs of beach material held together by the calcareous tubes of the marine worm *Serpula* are exposed at low water in Laguna Madre south of Corpus Christi Bay and in Baffin Bay. Barnacles encrust it.

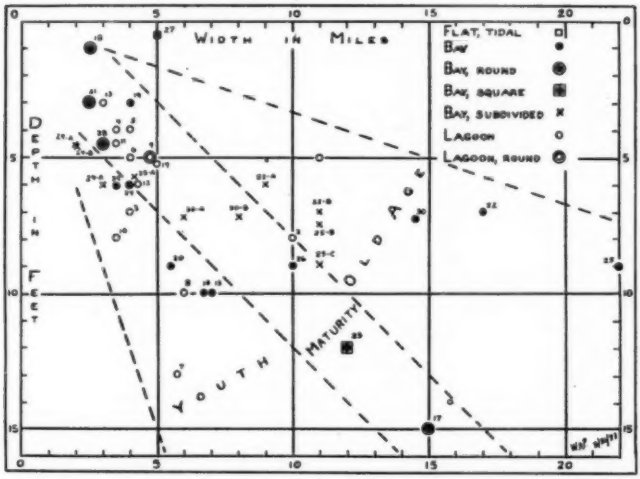


FIG. 7.—Width-depth adjustment and age stages in bays and lagoons of Texas south of Sabine Lake. Profiles from United States Coast and Geodetic Survey charts (1881 data) measured on N. 45° W. Diameters are platted and identified by numbers shown on Figure 2. Letters following figures indicate parts of bays separated by reefs. Nos. 1–14, 25-A are from coastal lagoon; Nos. 15–26, 28–30 are bays; No. 27 is a wind-scoured tidal flat (Saltillo Flats). Boundaries of age stages shown by dashed lines; areas outside dashed lines would contain estuaries, channels and tidal flats—basins not acted on by same group of forces as bays and lagoons.

These reefs, and some limestone reefs which seem to be largely a chemical precipitate, occur in an area of greatly fluctuating salinity. Oyster reefs occur chiefly in areas of more uniform salinity.

Such inland lakes and lagoons as are found in the flood plains of Nueces (Fig. 16), Mission (Fig. 11), and Guadalupe rivers were formed by the rapid down-stream advance of deltas into former bay heads, leaving parts of old stream channels and of former bay areas unfilled for a time. Thus, Nueces Bay has been filled by deltaic materials as far up as Calallen, 6 miles above the present head of the

bay. Flood-plain deposits have built the delta to an elevation of 5 feet.

The head of Lavaca Bay has been similarly filled by Lavaca River and Garcitas Creek to Vanderbilt, a distance of 7 miles. This bay-head delta deposit is marked on soil maps by Lomalta soil.

Width-depth adjustment in Tidewater basins.—Where reefs, bars or spits have been thrown across funnel-shaped estuaries and bays and at local constrictions formed by spurs of entrenched meanders (Figs. 11,

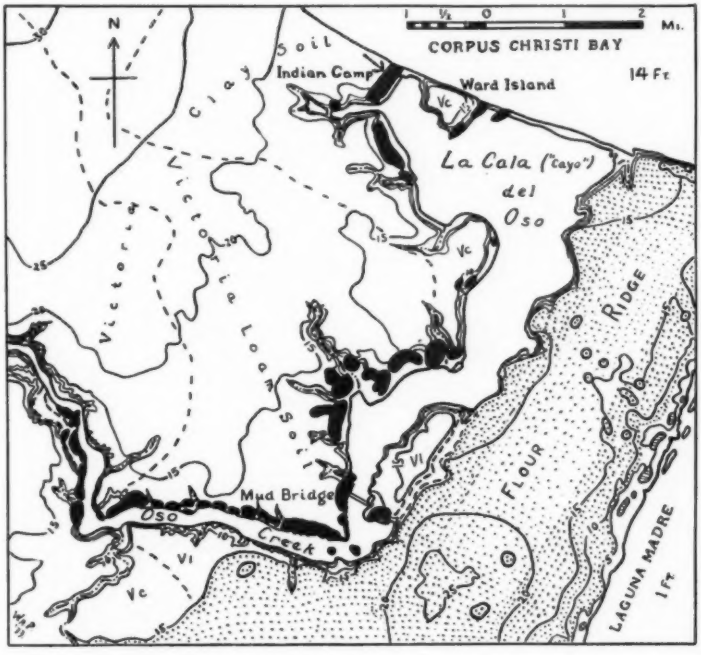


FIG. 8.—Clay dunes on lee shores of Oso Creek estuary (*La Cala*, locally "*Cayo*," *del Oso*). Black ovals, clay dunes; dotted area (Flour Ridge), a section of mature offshore bar composed of dune-sand resting on Beaumont clay at 8 feet above sea. A few sand dunes (dotted closures) shown on bar; along its east shore in coastal lagoon (Laguna Madre) are beach ridges (lined closures) on tidal flats and low shores. Contours (5-foot) from Oso Creek Quadrangle. Soils from Corpus Christi sheet (Mangum and Westover, 1909); Victoria loam area is distributary deltaic tongue of ancient Nueces River. Ward Island and mainland are Beaumont clay formation. Former channels of Oso Creek below the 15-foot contour are shown by dashed lines. Arrow at "Indian Camp" indicates principal site of Karankawa Indian tribe in this area and large amount of camp débris on top of clay dune. At Mud Bridge is Indian débris interstratified with dune material under several feet of cover. Burials excavated at each site (Martin 1930a).

15), the narrower, more inland portions of the bays have acted as settling basins for stream sediments, and the restricted force of the winds blowing across their narrow basins has not produced deep wave scour of their bottoms. The wider bay segments have stronger winds and waves and remain deeper, or are scoured deeper, than the narrower bay segments farther upstream. Thus, the west end of Nueces Bay above White Point is 2 miles wide and extremely shallow, much of it less than 1 foot; the east end of the bay, 4 miles wide, has a maximum depth of about 3 or 4 feet. As we pass between the large spits at the mouth of the bay, immediately north of the town of Corpus Christi, we find a bar and submerged scarp separating Nueces and Corpus Christi bays. The latter is 15 miles in northwest-southeast diameter and 14–16 feet deep over its broad, shallow, pan-like basin.

From these figures a rough relationship of width to depth is suggested and this is found to hold for all permanent water areas of South Texas more than 2 miles wide—the depth in feet being nearly equal to width in miles along northwest diameters in bays of a *mature* stage of development (Fig. 7). Some long basins, as San Antonio, Lavaca, and Galveston bays, are divided into two basins by submerged, median reefs. The ratio holds for these subdivisions considered as separate basins. Such subdivided bays are classed as *old*. *Young* bays are also found. These have excessive depths as compared with width (though none more than 10 feet). The existence of these relationships indicates an approximate adjustment between sedimentation and erosion to have been reached in the tidal basins of South Texas. Maximum and minimum ratios of width to depth (miles to feet) of 3:1 and 1:3, respectively, are represented. The northwest-southeast diameter has been chosen in comparing bay profiles because of the great predominance in annual strength of the southeast wind (Fig. 9).

Clay dunes.—Where tidal flats or playa bottoms with silty sediments are exposed to the drying south and southeast winds of the warm months and to periodical wetting by saline waters in the semi-arid and dry sub-humid zones of South Texas dunes of clay (Coffey, 1909; Coffey, 1912a; Beck and Hendrickson, 1928) are formed on the lee (northwest, north, or west) sides of the basins, either out on the flat or at the shore line (Figs. 4, 5, 8, 12, 14, and 10).

These dunes are distinct in form, origin, lithology, soil, vegetative cover, and physiographic locations from sand dunes. They are produced when clay chips covered, in cases studied, by mats of dried algae (pond slime) form on "sun-cracked" mud flats, curl at their edges and are blown shoreward by the wind. The disintegrating (deflocculating) action of the sea salts on the clay allows the silt to break down

into small particles. As these trains of particles are blown over the mud flats they resemble armies of ants. Stronger winds may raise dust clouds, some of the material of which lodges on the dunes and in their vegetation. The rolling particles, however, are all stopped along the shore of the basin or by vegetation on its exposed bottom. The first ensuing rain wets these accumulations of loosely aggregated clay particles to form ridges of clay. By gradual accumulation, ridges, or dunes, as much as 30 feet high and as much as a mile in length are

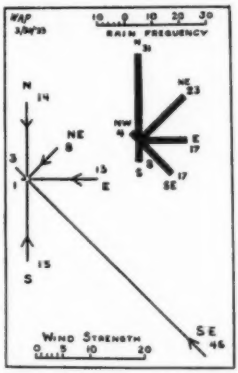


FIG. 9.—Wind strength and rain frequency at Corpus Christi. Data from United States Weather Bureau. Relative strength of wind (in percentage of all winds) derived from products of squares of average hourly velocities (1923–30 period) multiplied by average duration for each wind in percentage of time (1923–31 period), as developed by Price. Heavy lines show frequency of rain occurring with designated winds, expressed in percentage of total annual rainfall (1920–22 period), as developed by J. P. McAuliffe, United States Weather Bureau, Corpus Christi. Dominance of southeast wind in clay-dune formation shown by position of dunes at Oso Creek and relation of north winds to rain frequency and high tides.

produced. These dunes are steepest and most bare and gullied on the basin side, and slope gently on the lee side.

Distribution of clay dunes in South Texas.—The clay dunes may be elongated parallel with the shore line, or perpendicular to the average direction of the southeast and south winds. Many of the latter project from the mainland shore of Laguna Madre in Willacy and Cameron counties as 30-foot ridges several miles long and of varying widths. The village of Point Isabel is located on a coalescing group of clay dunes and has given its name to the soil which distinguishes them, Point Isabel clay (Fig. 10).

North winds, while strong, are accompanied by rains and high

FIG. 10.—Clay dunes on Rio Grande delta and in saline "mud flats" of lee side of coastal lagoon (Laguna Madre) at Point Isabel, 115 miles south of Corpus Christi. Point Isabel Quadrangle, 1-foot contours. Town is on group of coalescing clay dunes. Spanish term, *loma*, hill, locally designates clay dune. Point Isabel clay soil covers dunes; Lomalta clay soil, the delta. Open-water areas are blank. Marine planation of delta and dunes is shown by bluff along north and east shore at Point Isabel and west to edge of map. Dune north of Yacht Club basin was formed from south. This small area shows probable subsidence of delta lands by compaction of sediments, loss of land by wave attack, and building of land by wind scour.

water and are not drying winds (Fig. 9). They produce no clay dunes in South Texas. East winds are weaker at lagoon shore lines and blow for shorter periods than the southeast and south winds. East winds may take part in building clay dunes. The southeast wind is equal in strength to 46 per cent of the combined strength of all the winds and is the controlling factor in clay-dune growth.

The most striking example of clay dunes in the Corpus Christi area is on Oso Creek estuary (Fig. 8). Here they form dike-like lines, 15–30 feet high, along north, east, and west shores, separated by gullies. They border Tule Lake, 5 miles west of Corpus Christi, on its north and west shores (Fig. 15). Clay dunes are abundant in the upper (south) end of Port Bay basin (Fig. 4), and a group occurs at the southwest end of Copano Bay, due south from the town of Bayside, where they seem to surmount bay-mouth bars of Flamingo Bay.

Clay dunes are characteristic of saline playa lakes, saline lagoons, and tidal flats from Copano Bay to Rio Grande. They are proofs of the efficacy of wind scour (deflation) on saline flats in a semi-arid climate including the dry half of the sub-humid belt in the immediate coastal area. They are found farther inland in the semi-arid than in the sub-humid zone of South Texas. The clay dunes have been observed only on Recent and Beaumont (Pleistocene) deposits. The more inland playas have not been investigated. Coffey (1909) shows that the humid climate of tidal flats of the Mississippi Delta does not permit clay dunes to develop, though they are abundant in the Rio Grande Delta area.[8]

NORMAL TOPOGRAPHIC FEATURES OF NON-DIASTROPHIC ORIGIN

With the physiographic background sketched in the preceding paragraphs, we may proceed to analyze certain topographic features of the area which have attracted attention in oil circles because of their unusual appearance or alleged diastrophic origin. Some of these have led to the drilling of wells for oil. The features of the Corpus Christi area which have attracted widest notice are the high bay bluffs, former convex profile of the upland across Nueces River Valley, isolated segments of the mature offshore bar, round bays and extensive saline flats in a portion of the coastal lagoon. The assigning of a non-diastrophic origin to these means that they are normal physiographic features not, in their form or position, revealing or suggesting the influence of abnormal dips or former fault scarps. Local, non-causal

[8] Oval ponds, some of large size, occur in Refugio County but are not saline playas. Ridges associated with them are not confined to lee shores and are not similar to the clay dunes. Some of these features probably originated in meander loops of rivers.

association with areas of diastrophic deformation may occur. Oyster and other mollusc shells on high bluffs and asphalt on gulf beaches have also been thought indicative of oil.

Round and equidimensional bays.—Salt columns of salt domes are known to be round or oval in cross section and many salt domes to be marked by surficial depressions more or less round, most of which presumably mark local subsidence connected with underground salt solution or with central down-folding of the super-salt materials. For

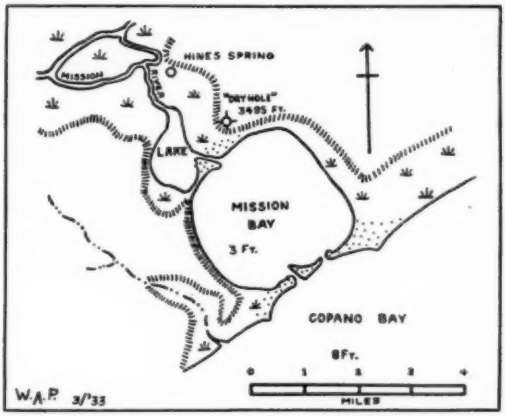


FIG. 11.—Mission Bay, a "round bay" of South Texas. Sketch, after United States Coast and Geodetic Survey. Bluff lines shown by hachures. Mission River and Melon Creek join and form island 3 miles northwest of bay. Rounded form of bay is given by contours of spits which project into drowned valley and by remaining parts of flood-plain deposits or tidal flats largely removed by marine planation. Hines' Spring issues from Beaumont beach-bed coquina. Swampy shore of Copano Bay east of Mission Bay mapped from reconnaissance soil sheet (Coffey *et al.*, 1912b) and is remnant of ancient Lake Copano. It carries Lomalta clay soil.

this reason, such approximately equidimensional basins as the west end of Nueces Bay, Mission Bay in Refugio County (Fig. 11), and Mesquite Bay in the coastal lagoon on the east line of Aransas County, have been thought by some to be of possible salt-dome origin.

When all the tidal water areas of South Texas are examined from a statistical standpoint it is found that nearly all those bays which have a ratio of width to depth of 1 mile to 1 foot are round or equidimensional (Fig. 7).

The round or equidimensional form of a bay is taken to be an expression of the adjustment between sedimentation and wave scour. Such basins are placed in the stage of maturity of bays. The attain-

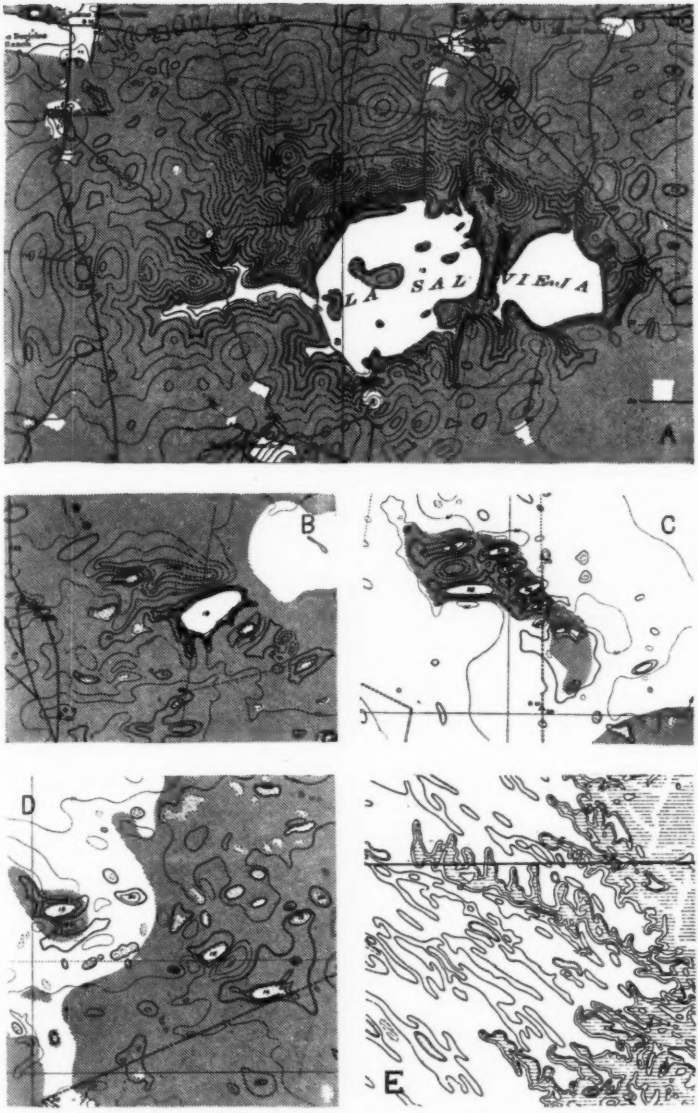


FIG. 12.—Saline playas and clay dunes. *A*, *B*, *C*, and *D* from La Sal Vieja Quadrangle; 5-foot contours; scale, 0.5 inch = 1 mile. Sal Vieja is largest playa, with clay dunes migrating northwestward across its basin and others forming large group on northwest (lee) side of playa. Point Isabel fine sandy loam (see Willacy County soil report) marks clay dunes and is closely related to Point Isabel clay soil of coastal clay dunes (Beck and Hendrickson, 1928). Some small islands and dunes in Sal Vieja playa bear Lomalta clay soil, probably indicating overflow at high-water stages and compound origin (Hawker and Simmons, 1929). *B*, *C*, and *D* show clay-dune-and-saline-playa series in N. 45° W. lines but with northeast to east axes of individual dunes and playas. *E* from Saltillo Quadrangle; 5-foot contours; scale, 1 inch = 1 mile. *E* is detail from Figure 14, shown twice scale of *A*–*D*, and showing dune-and-playa series from Saltillo Flats along entrenched sand-dune "blow-out" now eroded into underlying Beaumont clay with sand blown off toward northwest. Heavy shading indicates brush-covered areas; lined areas in *E* are mud flats; playas are blank or lined areas enclosed by depression contours.

ment of a rounded form has been accomplished by the disposal of sediments along the shores as deltaic flats, bars, and spits.

Mesquite Bay (Fig. 3) is thus wholly wave-built as to its nearly circular shores (see Coast and Geodetic Survey charts).

Mission Bay is a segment of a slightly drowned, entrenched river valley with parallel or slightly diverging walls which has been enclosed by spits projecting from the bases of an opposing pair of inter-meander spurs at the west end of the bay and from the mouth of the embayed valley of Mission River at the downstream end. The west shore of Copano Bay has been pushed inland by wave action to such a point that the length of valley left below this pair of meander spurs is approximately equal to the width of the valley. The rounding effect (as the bay is shown on Coast and Geodetic Survey charts) is given to this equidimensional valley segment by the curving shore lines characteristic of many spits. The valley walls seem to be slightly recessed opposite the central part of the bay, due to the lateral planation of Mission River before a recent slight submergence of the flood plain. These recessed wall areas are called *meander scars*. Projections between meander scars are called *inter-meander spurs* (Figs. 15, 16). On airplane photographs, the bay seems square. This appearance may be due to the visibility of under-water deposits and the lack of emphasis of the water line on photographs taken vertically from a considerable height.

The shallow west end of Nueces Bay is an irregular pentagon in outline, with a suggestion of circular form. The curves of this irregular bay are produced by the edge of the Nueces Delta on the south and by the meander-scar walls of the west side[9] of White Point Peninsula, an inter-meander spur (Fig. 15). Recessed valley walls here are meander scars.

Corpus Christi Bay is also sub-circular in the outline of its western half, but is too wide (12–15 miles) to receive serious attention as a salt-dome prospect. The writer believes that its curves are due to the recession of its bluffs under marine planation of the strong southerly and northerly winds and to the tendency for mature bays to develop curved shore lines as an expression of the balance between sedimentation and erosion. The formation of the large spits at the junction of Corpus Christi and Nueces bays shows the larger bay disposing of its sediments along its marginal areas so as to leave the broad central basin at the depth of adjustment (1 foot to 1 mile ratio; Fig. 3).

High bluffs.—If effective marine planation of shores is granted,

[9] It will be shown that the northeast and east sides of this basin seem to reflect diastrophic structure.

and if the principle of adjustment of the forces active in bays has been correctly applied, the occurrence of high bluffs at Corpus Christi (Fig. 13) is merely a measure of the balance between drowning and entrenchment in Nueces River and of the subsequent planation of bay shores into the area of a prairie sloping 2.5 feet per mile.

If the bay bluffs at Corpus Christi (35 feet above sea) are a few feet higher than those at other bay shores equally distant from the coast, as at Bayside on Copano Bay, near Austwell[10] on San Antonio Bay, and Magnolia Beach[10] on Lavaca Bay, it is because the town of Corpus Christi lies on the ancient distributary ridge of Nueces River which is elevated 15–20 feet above adjacent inter-distributary areas of the Beaumont Terrace.

Convex delta profiles.—As at Corpus Christi, vertical profiles drawn across ancient distributary ridges and broader deltaic deposits rising from the Beaumont or the Ingleside terrace, if not interpreted in the light of their deltaic origin, could be mistaken for surface elevations caused by diastrophic movement below. The convex front of this old delta might seem to exhibit "regional slopes" because it covers most of Kleberg, Nueces, and San Patricio counties, a front of 60 miles (Fig. 3).

Mound-like parts of distributary ridges.—Without detailed topography covering a wide area, many such features might be mistaken for mounds caused by diastrophic movement. Branching ends of distributary ridges may, after erosion, become isolated mounds. Scarps appear on unequally weathered and eroded sides. Lateral erosion of gully and arroyo valleys has isolated segments of these scarps which suggest (probably falsely) the influence of folded or warped strata below.

If mound-like loops of natural levees were formed where ancient streams were turned aside during local warping, these would reflect diastrophic structure, although such mounds would be of aggradational origin.

Sloping bottoms of abandoned basins.—If lowest elevations west of segments of the mature offshore bar be taken as a profile, a series of northeast "regional gradients" could be assumed which, however, are merely physiographic in nature.

For example, west of Flour Bluff Ridge, Laguna Larga is a part of the 10–15-foot Ingleside Terrace which has here not been entrenched by later streams or bays. South of Laguna Larga a distributary ridge

[10] The writer has no measurements of the bluffs at these two points but it is frequently asserted that Corpus Christi has unusually high bluffs. The bluff at Bayside is lower than that at Corpus Christi, as are those of the other towns named.

of Nueces River has an elevation of 5–15 feet or more. Six miles north of the Laguna is the shallow basin of the estuary of Oso Creek (Fig. 8), probably with a deeply silted central arroyo channel. Thus, a northward-dipping surface gradient occurs here.

West of Live Oak Ridge and Peninsula, the floor of Lake Copano slopes from the top of the old Nueces distributary south of Ingleside, at 20 feet above sea, to the bottom of Copano Bay, 9 feet below sea (Fig. 4). This gives a down slope of 29 feet toward the north in 15 miles.

Segments of mature offshore bar.—Several attempts have been made to find oil on this sand ridge. Shallow test wells were long ago drilled on it on both sides of Corpus Christi Bay. A deep test, the United North and South Oil Company's Kate Edwards No. 1, was recently drilled to a depth of 5,585 feet on Lamar Peninsula without reported showings of oil or gas. At these places, the ridge or mound shape of the bar, combined with the presence, at Lamar Peninsula, of mollusc shells on the upper surface of the bar, on bluffs overlooking the shore, led to the supposition that they represented uplifted areas. The fact that there is a ridge of Beaumont clay under the sand ridge has been used as evidence of folding or faulting. Marine planation on each side of the bar has produced and is maintaining parallel, oppositely facing scarps of recent origin cut in Beaumont clay.

A physiographic feature, such as this bar, 100 miles long and several miles wide, may be expected to overlie, at some places, areas of local deformation, but the occurrence of the bar itself with its associated bluffs is no guide to the location of such postulated oil-prospect areas. A section of this bar was made a portion of one of Deussen's postulated lines of anticlinal folding (1924, Fig. 33), which, however, he did not offer as anything but a suggestion in an area of little evidence for the discovery of diastrophic features. Associated rocks at water level will be described as soil or lagoonal deposits of recent origin.

The bar itself does not seem to reveal evidences of local crustal movement.

Mollusc shells above sea.—Though oyster and other mollusc shells may be thrown by waves to considerable heights above sea on some coasts, 3–10 feet seems to be about the upward limit of shells of beach origin in this area. The Beaumont clay contains, in places, foraminifers, shell marl, and oyster shells. These shell beds are not known to exhibit local deformation within the area of the six topographic maps around Corpus Christi, unless oyster beds reported in water wells at shallow depths in the Saxet oil and gas field show dips greater than normal.

Another class of occurrences of mollusc shells has led to the assumption that they represented "raised beaches." Heaps and large areas of oyster, conch, and mussel shells (Jones, 1928) are found abundantly on the ground surface and at depths of 1 or 2 feet in soil along all high bluffs from Calallen and Odem, 13 miles up the Nueces River Valley from Corpus Christi, as far north as Matagorda Bay (Gatschett, 1891), and southward into Mexico at least as far as Tampico. Similar heaps are found sparingly as far north as San Jacinto Battlefield, near Houston.

Obviously, such a widespread distribution of "raised beaches" would have no local significance, though many geologists have come to such a conclusion from too narrowly confined investigations.

The distribution of these shells corresponds with that of the historic occupancy of the shore areas by the mollusc-eating tribe of fisher Indians, the Karankawas (Gatschett, 1891). Martin (1930a, 1930b) has surveyed many miles of the shore lines of Copano, St. Charles, Aransas, Redfish, and Corpus Christi bays, making detailed archaeological examinations of the shell heaps and associated Indian burials and mounds. He found débris of Indian pottery, stone and bone clods, and notched bones of game animals and men. The writer has also observed oyster shells slaked and blackened by fire. The Karankawas included cannibal feasts in their ritualistic observances and many disassociated skeletal parts suggest butchering of human bodies. Many large conch shells seem to have been cut to take out the snail or crab inhabiting it.

The writer has checked these surveys at many points and mapped the shell heaps with plane table in the White Point oil and gas field. All shells are within a few yards, rarely as far as 200 or 300 yards, from bluffs overlooking water areas or from former water areas, such as the silted head of Nueces Bay below Calallen. The heaps of shell occupy many intermediate situations below the high bluffs on terraces or hill slopes and all are at well drained locations. They do not form a definite stratum as claimed by some (Jones, 1928). All examined contain Indian camp débris. Similar material is bedded in with clay dunes in the Oso Creek area (*Science News Letter*, 1930). (See Figure 8).

If oyster shells on the surface of Lamar Peninsula, for example, were the result of change of sea-level, why should they be found only at the edges of the sand ridge and not also over its top? There is no evidence favoring growth of these shells *in situ*. The Indian shell heaps contain at least two species not now found in the bays, al-

though Jones (1928) found them on beaches, probably in middens.[11]

Rockport limestone.—Deussen mentions "1 foot of hard, pinkish gray sandy limestone with a nodular structure" exposed on the beach at Rockport, Aransas County (Deussen, 1924, p. 112) as having a possible connection with a salt dome or anticline at that point. Search of the beach of the coastal lagoon as far south as Baffin Bay reveals that calcium carbonate is being deposited in certain areas, as a chemically precipitated binder of beach material, also in organic reefs formed chiefly by marine worms (*Serpula*), and as a matrix of impure sandy beds slightly indurated and containing a few small mollusc shells. Other observers report the deposition of salt and gypsum in the lagoon at many places from Baffin Bay to Tampico (Baker, 1929; *Corpus Christi Caller-Times*, 1930; 1931). It is not established that the shell-bearing sandy limestone at Rockport is not a Beaumont bed re-excavated along the beach, since such cemented sandy beds (although without shells) occur in Beaumont clay at a few other localities in the area; as on Oso Creek, at Angelita Switch near Odem, and in the south bluff of Nueces Valley, 5 miles west of Calallen.

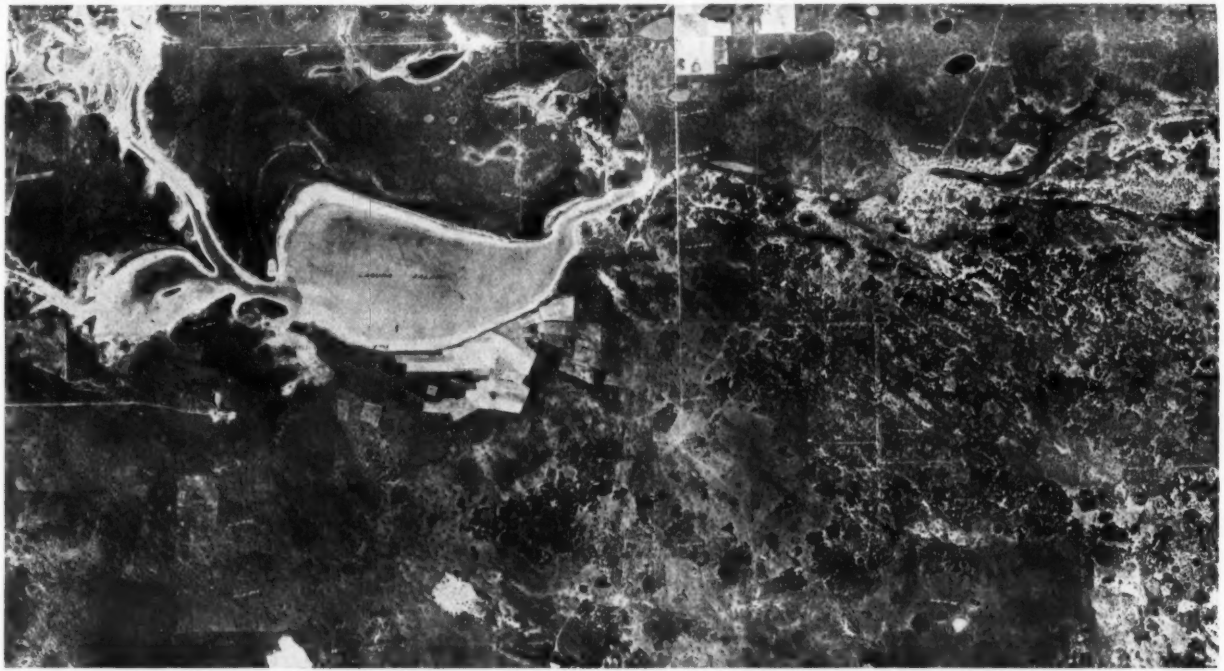
Other mineral deposits of Laguna Madre.—Manganese is being deposited as black hydrated oxide in the beach sands of the area. Brown, weathered nodules of the material occur in dune sands and have figured in early "geologic" prospectuses of the area as an evidence of "local mineralization." The occurrence is similar to, or identical with, "bog manganese" in origin.

Local reports of phosphate accumulations in Laguna Madre were based on fish bones and—it is said—on the occurrence of phosphatic mollusc shells in beach deposits.

Commercial deposits of this origin would indicate uplift of a highly phosphatic beach bed and its prolonged leaching with deposition of phosphatic nodules at a lower depth. No such occurrences nor evidence of such history have been discovered by local geologists who have examined the deposits.

"*The Oso,*" as the area in and around the estuary of Oso Creek is called, has long been favored in local lore as a "likely place for oil" because of its "rough country" and varied scenery composed of such unusual elements as entrenched, meandering tidal estuaries; the mature offshore bar; dike-like rows of clay dunes; short, bluff-wall drains; and great heaps of Indian shell and other débris (Fig. 8). Asphalt obtained by the Indians from the gulf shores is found in and

[11] Clyde T. Reed, professor of biology, Texas College of Arts and Industries, Kingsville, Texas, says that *Venus mercenaria* Linnaeus and *Macrocallista nimbosa* Solander occur numerously in the middens but "are not even occasionally found [living] around here to-day."



(Photographed from the air and copyrighted by Edgar Tobin Aerial Surveys.)

FIG. 13.—Laguna Salada, Brooks County, southeast of Falfurrias. Reproduced by courtesy of Edgar Tobin Aerial Surveys from their 23 S., 16 E., grid square. Dune sand dotted irregularly with live-oak vegetation east and southeast of lagoon is at northeast margin of Kenedy County dune field (*erg*). Dunes have dammed valley of intermittent arroyo formed by confluence of Baluarte (from west) and Palo Blanco-Cibolo (from northwest) arroyos. Palo Blanco Arroyo also called San Antonio Creek. Crescentic dark lines northwest of west end of playa lake have not been investigated, but are presumably clay dunes. Deltas of arroyos have divided west end of playa into two lobes. Gypsum quarry on Gyp Hill shown by spot with heavy shadow of quarry wall along its west side. Gyp Hill is commonly interpreted as salt-dome surface mound. Southwest corner of photo is at 27° 7′ 30″ N. Lat. and 98° 7′ 30″ W. Long. Scale: approximately 1 inch = 5,500 feet.

decorating their pottery and fire-making trumpets (Pearce, 1932).

A local tradition states that Ward Island, the bay-mouth bar which ties it to land across the mouth of the estuary, and the clay dunes of its western shores, have all been raised from the ground in the past 65 years. However, Ward Island shows typical Beaumont clay with large caliche concretions of the same size, shape, and position as in the adjacent mainland and Indian camp débris is found in and on the dunes.

The choice of the clay dune at the mouth of the Oso as a principal camp site by the Karankawa Indians was undoubtedly decided, in part, by the occurrence of fresh water in ponds back of the clay dunes. Karankawa camp sites are also found on Ward Island.

Intra-meander mounds.—Ward Island is evidently a mainland remnant cut off by the entrenchment of a loop of the meandering Oso Creek. The downstream half of the meander has now been destroyed by marine planation of Corpus Christi Bay, unless it is preserved below sea as a silt-filled channel. Similar intra-meander mounds occur 3 miles west of Calallen in Nueces Valley as terrace outliers.

Intra-meander spurs are associated with diastrophic structures at White Point and Viola (Fig. 15); less prominent spurs may not be. This question is further discussed under the head of Conclusions.

Asphalt on gulf beaches.—The testimony of old natives, as well as that of the common use by the shore-dwelling Karankawa Indians of pre-historic and historic times, of asphalt to decorate pottery and make fires, shows that the occurrence of asphalt along the beach of the young offshore bar must antedate the commencement of the shipment of asphalt, fuel oil, and crude oil, in quantity by vessels in the Gulf of Mexico. From several sources which seem to be reliable, it is reported that actual seepages of oil may be seen at the north end of St. Joseph's Island (Fig. 3) on the sand bar and in the coastal lagoon and gulf. Three shallow test wells were drilled there several years ago; the deepest was 2,560 feet. The asphalt is common and abundant at least as far north as Matagorda Peninsula and as far south as Padre Island. Its original source must have been either active oil seepages in the Gulf of Mexico,[12] or from asphalt eroded from the coast of South America or Mexico or from all these sources. Of recent years, barrels of asphalt come ashore, as well as waste oil from ships.

Contact of fresh and salt water along offshore bars.—Versluys (1931) shows that sand bars act as reservoirs of fresh water which, collecting

[12] Hayes and Kennedy (1903), pp. 104–8, Fig. 4, pp. 111–12 and Harris (1910), map opp. p. 6, p. 9, cite oil in the gulf. Oil residue, "copal," is reported by the survivors of the De Soto expedition, 1541 or 1542, from near Sabine Pass—note by C. L. Baker.

with a slight hydrostatic head, displaces the saline water of the sands and underlying beds laterally as well as horizontally, so that fresh water may be struck in wells in sharp contact with salt waters at appreciable distances from the sand bar (Price, 1932, Fig. 1).

This situation, of purely physiographic origin, has been used by some to advocate a fault along the west side of the mature offshore bar.

Playa basins not salt-dome depressions.—Two illustrations from south of the Corpus Christi area may be inserted here. La Sal Vieja and Sal del Rey, two large saline playas west of Raymondsville in Willacy and Hidalgo counties, respectively, were shown on early editions of the United States Geological Survey's oil and gas field maps of Texas as probable salt domes. Many geologists have speculated on their origin, wind scour being commonly credited with some or all of the topographic relief (Barton, 1926). (See Figure 12 A.)

Topographic mapping of that area disclosed that they are merely large and conspicuous examples of hundreds of playas of these and adjacent counties. The recognition of mounds on their lee (northwest) sides and out in the floor of Sal Vieja as clay dunes of windblown origin shows the mode of formation of the depressions. The volume of the dunes forms a significantly large fraction of the volume of the depressions. The form of the mounds and their Point Isabel soils are typical of clay dunes. They contain some sand in the dune material, but are not of the sand-dune type. A well drilled at the west shore of Sal Vieja by Alamo Drilling Company to a depth of 3,065 feet did not yield showings of oil or gas or salt-dome minerals. The writer does not know the results of geophysical surveys, if any have been made there. The ground water of this area is commonly saline beneath a surficial layer of fresh water. Salt blown in from the lagoon, with or without silt, must have been an important source of salt in the ground water. Salt grains have been found to form nuclei of fog droplets (*Science News Letter*, 1932), and much salt should accumulate in the sand plain of South Texas from fogs, although these are relatively infrequent.

In areas where saline ground waters occur, or where evaporation and lack of drainage cause concentration of saline minerals from waters of originally slight mineral content, saline playas will be formed by wind scour and their shapes determined or modified by the winds.

Where, however, saline waters from buried salt masses reach the soil zones in a semi-arid area, we would expect the formation of saline playas whose forms might be determined, in part, by structural deformation in the strata beneath. These would develop clay dunes and be modified in shape by wind scour.

Study of 300 or 400 saline playas flanked by clay dunes in the Sal Vieja area (Figs. 12, B, C, D) and northward to Falfurrias indicates that the larger saline playas of wind-scour origin occur toward the inner margin of the Beaumont clay outcrop, indicating that their size is related to their age.

Laguna Salada, near Falfurrias, is an elongate, triangular saline playa formed behind a dam of windblown sand in the valleys of the intermittent Baluarte and Palo Blanco arroyos (Figs. 2 and 13).

It seems to function as an evaporating pan for the waters of these arroyos. The association of the playa with the adjacent Gyp Hill mound, with its gypsum deposit, need not indicate salt-dome origin of the saline ground water here. Barton has described the salt-dome and wind-scour features of this locality (1924). This playa is typical neither of salt-dome depression basins nor of deflation playas of South Texas, but is a dammed stream valley modified by wind scour and a stream delta. Airplane photographs seem to show extensive clay dunes on its northwest shores, which are roundly indented, showing the influence of deflation and the incipient development of a more typical deflation-playa outline due to wind and wave attack on its lee shores since the sand dunes dammed the stream. Whether the concentric ridges northwest of the playa represent former shore lines or merely clay dunes has not been investigated on the ground by the writer.

Shoaling in Laguna Madre.—A second illustration from south of the Corpus Christi area is used because of its possible misinterpretation by those who have not made a special study of the shore area of South Texas.

The writer's interpretation of the bearings of the free ends of spits (Fig. 3) shown on the Coast and Geodetic Survey charts is that there is a dominant southward (counter-clockwise) shore drift of sediment in the coastal lagoon from Matagorda Bay to the 27th Parallel of Latitude, south of Baffin Bay. From Point Isabel northward to this parallel, no marked shore drift in the lagoon is revealed, but more of the small spits mapped point northward than southward (Fig. 14).

A meeting of drift currents in the lagoon near the 27th Parallel is indicated. The meeting of currents caused deposition and shoaling of the lagoon. These results are in accord with those obtained by a study of the data on the gulf shore drift which indicate a meeting of currents on the east side of the young offshore bar in the same vicinity and the collection there of driftwood in large amounts. Careful study of wind directions and strengths shows that the change in curvature of the young offshore bar, Padre Island, at this point is the cause of the dominance of the winds on the inner lagoon shore line north of 27°

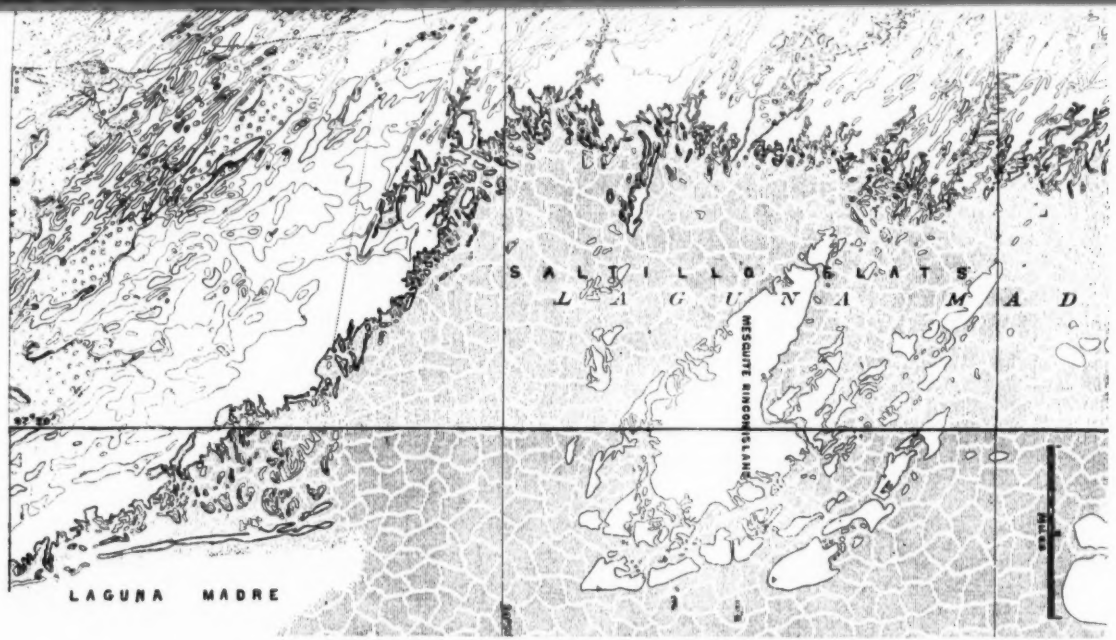


FIG. 14.—Wind-scoured, mud-flat indentation of coastal lagoon (Laguna Madre) here called "Saltillo Flats." Saltillo Ranch and Lopena Island quadrangles, 5-foot contours; 55 miles south of Corpus Christi. Kenedy County dune field (*erg*) of ridge-type sand dunes (N. 45° W. axes) in knife-like chains of dunes seen crossing southwest corner of figure and originating near shore along entire west side of figure. *Erg* has been partly blown inland from narrow zone along Saltillo Flats, many former "blow-out" depressions between sand dunes being now entrenched by erosion into Beaumont clay to water level (mean high tide) and below, producing fjord-like shore line. Saw-tooth branches of these entrenched blow-out "canals" are formed by series of clay dunes and saline basins (Fig. 12E) produced by wind scour behind clay dunes, with repetition of dune-and-basin pairs. Clay dunes trend dominantly at right angles to these sand-dune ridges, are short (commonly 0.1 mile), and confined to shore areas and inland saline flats. Mesquite Rincon Island group are possibly mainland remnants; back of long bar in southeast corner of figure is cove dotted with clay dunes. Southeast wind is dominant and controls trends of dunes, playas, "canals," and islands. Bar in southeast corner was formed by shore-drift current south; Saltillo Flats represents shoaling where this current meets current from north past mouth of Baffin Bay. "Canal" west of letter *S* in *Flats* is enlarged in Figure 12E.

North Latitude, and for the dominance of the southerly winds south of it, so far as their influence on the shore drift is concerned.

This meeting of currents has produced a shoaling of the lagoon along an undetermined long stretch of the lagoon south of Baffin Bay. At the same time Padre Island has advanced within about a mile of the mainland (Fig. 2; contrast Fig. 3, the old mapping) at the mouth of Baffin Bay (*Texas Game, Fish, and Oyster Commission*, 1930, p. 56). The shoaling covers a length of 15 or more miles along the center of the east side of Kenedy County.

The writer has heard it advocated that this shoaling, shown on the Lopena Island Quadrangle topographic sheet (United States Geological Survey), is an evidence of the passage of a regional uplift from central Brooks County to this point. No subsurface evidence seems to exist for this belief, since Kenedy County is almost wholly unprospected.

Saltillo Flats.—Inland from the lagoon shoals described is an abrupt indentation of the mainland, here called *Saltillo Flats*. It is a "tidal" flat now exposed for long periods during each year. Wind tides only are appreciable in the lagoon. Lopena Island, Mesquite Rincon Island, and numerous smaller islands remain as permanently dry areas less than 5 feet above sea (Saltillo Ranch Quadrangle sheet). (See Figures 12E and 14).

The low shore line of Saltillo Flats at mean high water is indented and minutely fjord-like. Narrow, canal-like channels extend back as far as 3 or 4 miles into the mainland. Short branch canals enter the main canals almost perpendicularly. Innumerable, small clay dunes with small playa depressions on their east sides dot the shore and inland area among the channels. It is seen that these dunes are arranged with considerable regularity. The clay-dune axes trend dominantly N. 70°E. to E. Series of alternating playa-and-dune pairs form lines N. 45°W. That this is a normal habit for clay dunes is seen on most of the topographic sheets of this area (La Sal Vieja, Armstrong, Saltillo Ranch, Tarida Ranch, Lopena Island; Fig. 12 B, C, D).

Clay-dune series are formed where wind rising over a dune forms an eddy behind it, scouring a new basin and forming a new dune leeward and the process is repeated several times.

The salt-laden silt from the lagoon flats south of 27°North Latitude and from Saltillo Flats has been blown inland, moving in large part as clay dunes, which retreat, though slowly, leeward under the dominant, southeast on-shore drying wind. This action has resulted in the erosion by wind-scour (deflation) of the area of Saltillo Flats out of the mainland composed of Beaumont clay overlain by sand-plain

alluvium. The sand has moved off to form typical sand dunes interior to the clay-dune coastal zone. Coalescing of playas of adjacent series has formed the branch "canals." The main "canals" seem to be of wind-scour and gully-erosion origin inherited from the long, narrow "blowouts" or depressions between the knife-like sand-dune ridges of the great dune field of Kenedy County which has moved off inland from the area of Saltillo Flats as the latter was excavated by clay-dune activity.

The shoaling of the lagoon is, therefore, the source of Saltillo Flats, of the N.45°W. and N.45°E. fjord-like tidal gulleys and playas with their associated clay-dune series and of the great *erg* or dune field of long, ridge-type sand dunes (Aufrére, 1931; Bryan, 1932) which extends N.45°E. from Saltillo Flats to Sarita and Falfurrias, 25 and 40 miles inland, respectively.

TOPOGRAPHIC FEATURES INTERPRETED AS SHOWING DIASTROPHIC DISTURBANCE

Concurrent topographic and structural slopes in two oil fields.—Subsurface study of the two oil and gas fields of the area, White Point and Saxet,[13] from well logs and from available reports on cores and cuttings, with a few determinations of cores from the marine zone of the middle Oligocene, reveals that the rotary drill is a most imperfect tool for the logging of these soft formations, when supplemented only by cores taken, from the point of view of subsurface correlation, very much at random. From a study of many well logs, however, some main structural features seem to have been determined.

The Saxet field seems to be an eastward-plunging, elongate structural nose with east-west axis. Faulting at the east end of the field is suggested by logs of the early, shallow gas wells, but these are too imperfect to yield definite evidence.

The northeast slope of the structural nose is paralleled by one of the steepest meander-scar cliffs of the entrenched Nueces River flood plain (Fig. 15). Yet, all similar meander scars of the valley can not be expected to reveal dipping strata. The axis of the nose seems to be reflected in the topography of the upland by the 45-foot contour where the latter is extended ½ mile down the slope of the upland beyond its normal-interval position (based on the average slope of 2.5 feet per mile for the upland). The apparent structural reflection is still stronger at the 40-foot contour which, though 1 mile or more beyond the limits of the field, as it is now known, is extended 1 mile beyond its normal position. However, both contours should be somewhat ex-

[13] Not including 1932 and 1933 development in west end of Saxet field.

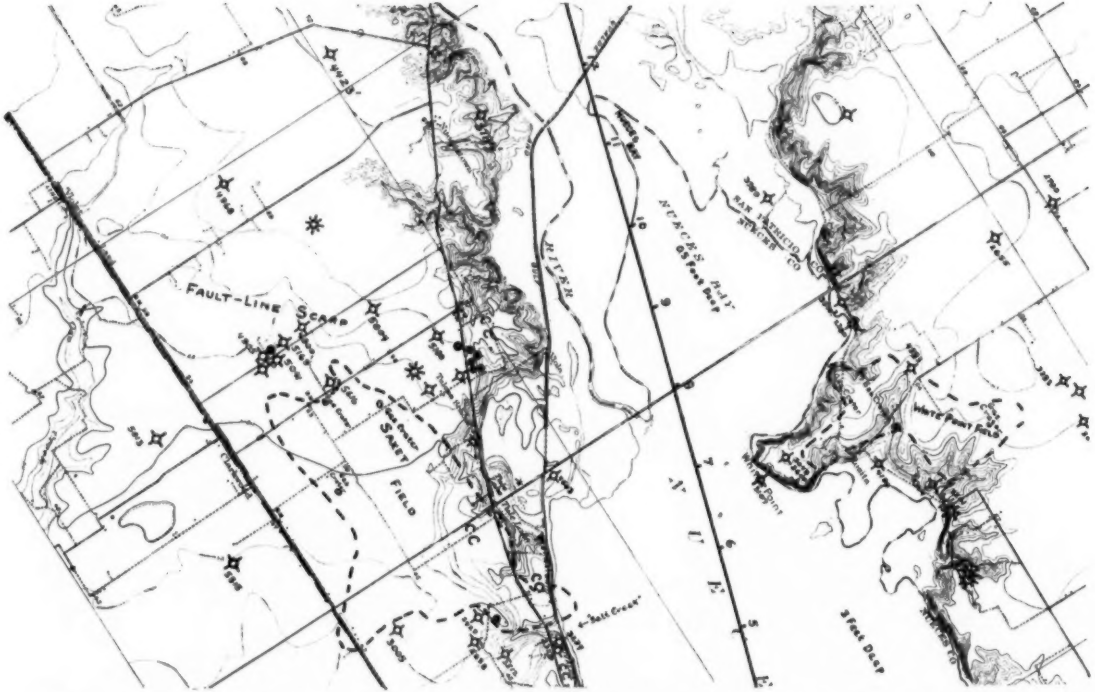


FIG. 15.—Drowned valley of Neuces River in area of White Point and Saxet oil and gas fields, with Violet-Viola fault-line scarp. Robstown and Corpus Christi quadrangles; 5-foot contours. Dashed lines enclose areas of oil and gas production as developed to June 15, 1933. Oil wells, black circles; gas wells, circles with 8 prongs; "dry holes," circles with 4 prongs. Scale, profile, and terraces as in Figure 16 (overlapped at Nuecestown, Miles 11 and 12). Flood plain is delta of Nueces River. Clay dunes enclose Tule Lake on north and west. Remnants of distributary ridges of ancient Nueces faintly indicated at edges of upland overlooking valley. Closure of 65-foot contour north of White Point field is beginning of abrupt northeast bend of distributary on up-dip side of structural nose. Marsh-floored meander scar east of White Point inter-meander spur suggests fairly recent invasion of flood plain by bay, either by change of sea-level or marine planation. It may be, however, merely tidal-flat development. Discovery oil wells, only, are shown inside field areas. "Dry hole" shown in re-entrant of west boundary of Saxet field, total depth 5,616 feet, is Gulf Port and Karona oil companies' Frank E. Bliss No. 3 which is reported to have shown several faulted cores between 4,000 and 5,000 feet with fault plane nearly vertical and separating sediments of unlike lithology and hardness. "Dry hole" southwest of Clarkwood may be completed as gas well; that southeast of village showed oil and gas but was mechanical failure.

tended because they loop around a convex ancient distributary ridge of Nueces River plainly marked by topography and soil pattern.

The argument for topographic expression of the nose is supported by the fact that the highest point on the east end of the nose is also a topographic high with one 5-foot contour closing and is isolated by adjacent, short, valley-wall creeks into a ridge 25 feet high (Fig. 17). The east slope of this ridge, that into "Salt Creek" at its foot, coincides with the beginning of the east slope at the end of the structural nose. On this ridge, inside the small closure, the writer located the discovery oil well of the field (Price, 1930b), the Saxet Oil Company's Dunn No. 6, which produced oil from 4,297 to 4,308 feet.

"Salt Creek" runs north in a gentle structural depression mapped on the 2,100-foot water sand. On the banks of this creek the discovery gas wells of the field, Pioneer Meaney No. 1, and Dunn Saxet Nos. 1 and 3 were drilled.

The White Point gas field has been contoured by the writer and others as a broad, dome-like nose whose southeast and southwest slopes are parallel with similar bluffs of the compound peninsula or inter-meander spur of White Point. Northwest closure is poorly, if at all, indicated by well logs. Subsurface contours drawn in such a manner that the minor details of surface topography were not in the mind of the geologist surprisingly revealed a coincidence between minor structural lows and the V-shaped valley-wall arroyos.

The discovery oil well of this field, still the only one making oil, is the Saxet Oil Company's No. 17 Rachal Ranch (Price, 1931). It was located by the writer $\frac{1}{4}$ mile back from the supposed crest[14] of a structural slope above a well which showed oil and salt water in a higher sand. The Rachal No. 17 made a heavy flow of gas with more than 100 barrels of oil on an early test in sand from 4,878 to 4,902 feet in depth. It is 2,000 feet northwest of the southeast bounding meander-scarp bluff of the field, and also about 15 feet below the upland in a bluff-wall arroyo.

Linear topographic scarp on Beaumont Plain associated with apparent offset in Nueces River terraces.—A conjunction of features believed to be abnormal in their relationships reveal, if correctly interpreted, the presence of a fault which crosses Nueces River between the White Point and Saxet fields. It is recognized that the evidence is not sufficiently extensive to be convincing beyond possibility of error. Yet the somewhat circumstantial evidence fits this interpretation and is, so far, in harmony with the production pattern of the field.

[14] *Crest* is used in the sense of the military crest, or line of junction of a steep flank with a flatter top.

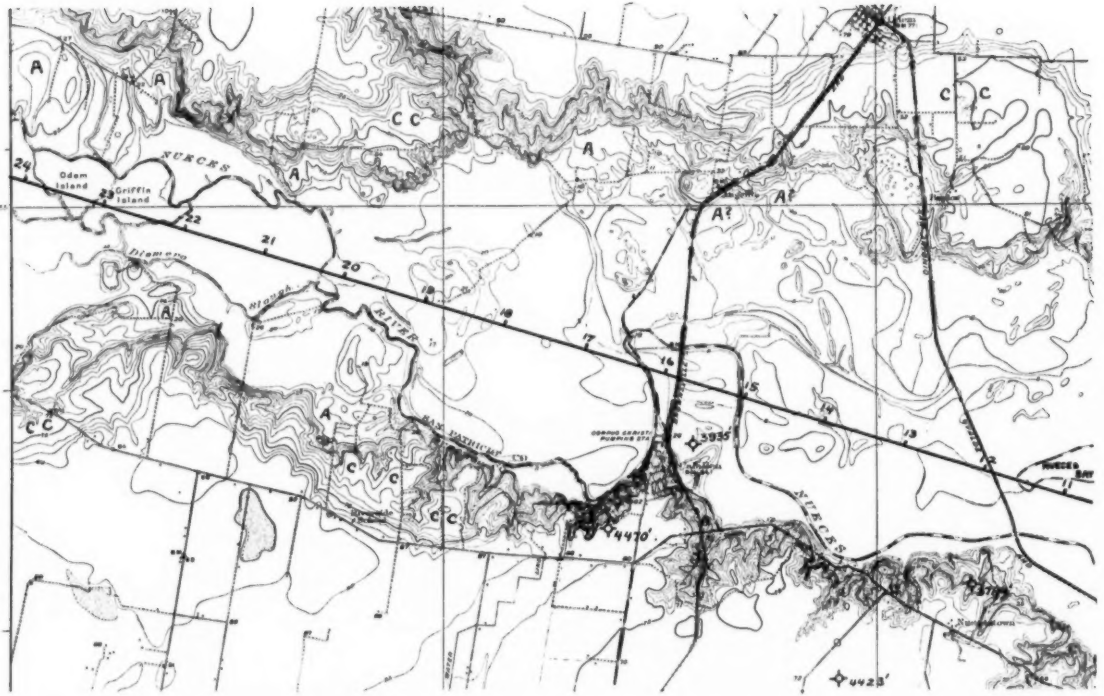


FIG. 16.—Nueces River valley and upland (Beaumont Deltaic Plain). Robstown Quadrangle, 5-foot contours. Scale of miles from mouth of Nueces Bay at Corpus Christi is profile line of Figure 17 (miles too short by 1.4 per cent). Terrace remnants shown in that figure are here designated *CC* (Corpus Christi) and *A* (Angelita). Relations of Angelita Terrace south of Angelita obscure, 2 levels and a scarp appearing. "Dry-hole" depths in feet (locations northeast and southwest of Nuecestown approximate). Other features: flood plain, flood-plain bar (Calallen to Angelita); intra-delta lakes of Nueces River delta; braided river pattern accompanying accumulation of "rafts" of logs and silt in channels (Odem and Griffin Islands); clay dunes with northerly and easterly axes associated with brackish-water basins and flats east of Calallen; intra-meander mounds (at Miles 18 to 21); inter-meander spurs (as Calallen, 15–80-foot contours) and meander scars; sand dunes on terraces at Baylor; V-shaped valleys of canyon-wall drains with alluvial fan of Hondo Creek; remnants of ancient distributary or distributaries shown by looped contours along edge of upland (marked by sandy soils); shallow, fresh-water playa lakes on Beaumont Plain without cliffed shores. Figure 15 overlaps Figure 16 at Nuecestown.

As was stated in the Introduction, there has been no opportunity for a study of the subsurface as revealed by wells recently drilled and it is preferable to defer this study until still more wells have been drilled. The description of the Nueces River terraces has been deferred to this point for study in conjunction with the topographic evidence for a fault cutting them.

Terraces of Nueces River.—A dozen or more narrow and linear, to broad and semi-circular remnants of river terraces with flat or gently

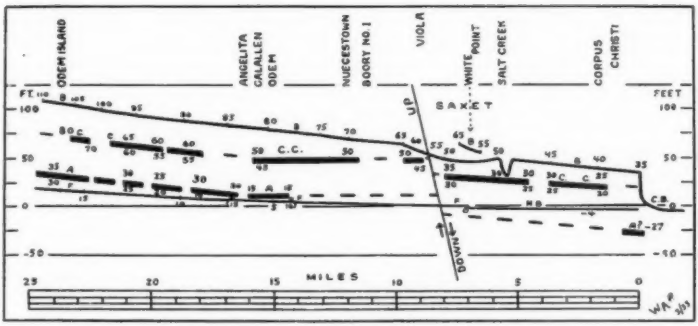


FIG. 17.—Longitudinal profile of Nueces River flood plain and terraces interpreted with fault of 15-foot vertical displacement at Viola (fault not studied in subsurface). *B*, Beaumont (upland) Deltaic Plain; *CC*, Corpus Christi Terrace; *A*, Angelita Terrace; *F*, flood plain; *NB*, Nueces Bay; *CB*, Corpus Christi Bay. Minor relief on Beaumont shown only in Saxet field; Beaumont profile taken from south canyon wall along distributary of ancient Nueces River; profile over White Point shown at 7th mile projected (at right angles) to plane of section. Distances along central axis of valley, with terraces projected on it at right angles. Bounding contours of terrace flats where determinable from topography shown by figures above and below line representing terrace; dashed lines show interpretation of former continuity of terraces.

sloping floors and bordered by meander scar cliffs are found cut into the valley walls of Nueces River between Odem Island and Corpus Christi. Intra-meander mounds which are terrace remnants stand out on the flood plain at several places in the mapped area (Figs. 15, 16).

The terraces show much more erosion west of Calallen than east of it; west of it they bear sand and sand dunes in many places. Both these conditions make the determination of precise levels of terracing difficult at these points. In the flood plain stand clay dunes and flood-plain bars. The former rise to 10 or 15 feet above sea or above the flood plain. The origin of some flood-plain mounds, as to whether they are built structures or erosion remnants, has not been determined.

The accompanying profile (Fig. 17) along the central axis of the valley shows the elevations and extent of terrace remnants believed

to represent the true former level of two terraces at measured points along the south valley wall or at equal distances from the central axis of the valley on its north side. In the profile, bounding contours of the terrace flats are shown and a few elevations from single contours as they cross well preserved terrace remnants. The possibility of errors of interpretation connected with identification of uneroded original terrace remnants and the determination of initial cross-valley slopes is to be recognized. The errors of this type could have no greater effect than to introduce west of Calallen some irregularities whose possible structural origin is not known, or possibly to introduce a third terrace below elevations of 50 feet above sea. If the level terrace southeast of Odem at 50 feet, here called the *Corpus Christi Terrace*, be corrected for a cross-valley slope not shown by it but of the same order as others of the area which do show such slopes, the height of its south end on the profile would be reduced only 5 feet. If we go further and assume the leveling of the Corpus Christi Terrace from Viola to Odem to be due to some normal depositional process, we still leave unexplained the isolated remnant standing at 50 feet at Viola. These interpretations seem not to fit the facts.

The most normal interpretation of the terraces is that they originally had a slope slightly less than that of the upland, which is here 3.4 feet per mile (75 feet in 24.3 miles in the profile). Using this as a guide and temporarily disregarding the level terraces near Odem, we find that the terrace remnants fall definitely into two gradients, the upper of which, occurring at Corpus Christi at 20–25 feet, is referred to as the *Corpus Christi Terrace*. This terrace has an over-all gradient of 2.16 feet per mile (47.5 feet in 22 miles in the profile). One lower terrace has been distinguished and will be called the *Angelita Terrace* from the 15–25-foot remnant best preserved between 1 and 2 miles N.70°W. from the 31-foot bench-mark at Angelita Siding, St. L. B. & M. R. R. The relations of the 10–15-foot shelf south of the same bench-mark are uncertain. It may represent a terrace elsewhere entirely removed by erosion. The slope of the Angelita terrace is 2.5 feet per mile (25 feet in 10 miles) for the part above water. A bed of oyster shell beneath bay silt between 17 and 27 feet below sea at the mouth of Nueces Bay is reported by construction engineers from piling driven for a bridge. The clay under the shell at 27 feet below sea may be the extension of this terrace. Clay bottom silt was found at depths down to 31.5 feet, 1,000 feet off Avery Point, a rounded point on the south shore of Nueces Bay, 3 miles west of Corpus Christi Bay. These depths of 27–31 feet seem to represent the same former flood plain.

If we use the clay beneath the oyster bed, 27 feet below sea at the mouth of Nueces Bay, as a part of the Angelita Terrace, we obtain the same gradient for a length of 25 miles over-all as we got for the above-water portion, or 2.6 feet per mile (64.5 feet for 24.7 miles). The flood plain has a slightly concave gradient curve which falls 18 feet in 18 miles to the mouth of Nueces River.

Violet-Viola Scarp.—Perhaps the most conspicuous scarp on the Beaumont Terrace in the area is that marked by the 55-, 60-, and 65-foot contours from 6 to 9 miles west of Corpus Christi between Violet Siding on the Texas Mexican R. R. and Viola Siding on the San Antonio, Uvalde, and Gulf R. R. The gradient of this scarp varies from 5.8 feet per mile to 20 feet per mile. The scarp ranges from 1.25 to 1.50 miles in width. It has not been traced south of Oso Creek but it may extend 1 or 2 miles south to the flank of the Robstown-to-Laguna Larga distributary. It is prolonged in the 50-foot meander-spur wall of the Viola terrace remnant. Including this prolongation, it has a length of 5.5 miles south of Nueces River.

If we follow the northeastward extension of this scarp on its N. 45°E. bearing, we find several topographic scarps with the same alignment, some of which have no more than a possibly indirect connection with the faulting. A submerged bar or low scarp crosses Nueces Bay between protuberances formed by the Nueces River Delta and White Point. The bar is visible when strong north winds have driven the water out of the upper bay. This bar was probably formed by normal processes of bay sedimentation between these closely approaching protuberances of the valley.

Northeastward prolongation of Violet-Viola fault?—Across Nueces Bay, the White Point Peninsula has a slope, shown in the profile (Fig. 17) by a disconnected line, identical with that of the Violet-Viola Scarp along the river bluff. Essentially the same scarp is formed at the northeast edge of the White Point field, 3.5 miles from the Point. These scarps are interpreted as controlled by the fault or by an associated flexure. Three miles farther northeast in the vicinity of the West Portland Gin, the Pickett *et al.* Whitworth No. 1 was drilled on a large sand dune in a loop of the 55-foot contour to a depth of 3,325 feet and the Mission Drilling Company's Morris No. 1 was located a little farther upslope on the 10-foot scarp between the 50- and 60-foot contours and was drilled to a depth of 3,004 feet. These wells reported showings of oil at about 3,100 feet. They seem to be located on features associated with a distributary of the ancient Nueces River deflected northeastward by the White Point structure.

From the West Portland Gin locality to Taft the distributary of

the ancient Nueces appears to be marked by the low topographic ridge caught by the 55-foot contour. It is covered by sandy loam soil. Branches of this distributary seem to have flowed, one southeastwardly from West Portland Gin toward Portland and Gregory, and another northerly toward a point on the San Antonio and Aransas Pass R. R. 2.5 miles west of Taft (Fig. 3). Such broad distributaries are marked by irregular contours on the seaward slope, which is, in some places, several miles wide on this side alone. For this reason the identification of a possible fault scarp extending northeast beyond the White Point field becomes uncertain, the alignment of the distributary ridge confusing the picture. The course of the distributary may have been influenced by a fault scarp or by a warping of the prairie along, or in line of, the fault. At the north boundary of the Corpus Christi Quadrangle topographic sheet, at 28°North Latitude, a swamp is shown on the extension of the fault line and a low scarp, caught by the 40- and 45-foot contours, is shown 1.5 miles northwest. In the absence of detailed topography on the north, no decision can be made as to whether or not these features represent an eroded fault scarp. The abrupt turn of the distributary ridge at White Point and West Portland Gin to align itself with the fault is, however, highly suggestive of a prolongation of the fault from White Point to Taft.[15]

Fault offsetting river terraces?—The relation of the Violet-Viola and White Point field scarps to the supposed offset in the river terraces at Viola lend strength to the view that it is caused by a fault scarp, more fully discussed in later paragraphs. The profile of the Corpus Christi Terrace (Fig. 17) shows the writer's interpretation of an offset of 15 feet between the terrace remnant at Viola at 50 feet and the terrace remnant at Tule Lake (south of White Point) at 30–35 feet above sea, these points being separated by a length of 1 mile of valley wall where the Tule Lake abandoned meander has cut out the terraces.

West of this scarp, which is believed formerly to have cut the Beaumont Plain and the Corpus Christi Terrace and possibly the Angelita Terrace, there is an abnormal flattening of the terrace gradient for 7 miles, as is plainly shown in the great terrace remnant, on the north valley wall, 2 miles wide and 4 miles long, bounded by the 45-, 50-, and 55-foot contours lying immediately southeast of the town of Odem.[16]

[15] H. A. Noble has developed a method of identifying faults by such offset stream courses. Barton has shown offsetting to occur in small branches at fissure lines.

[16] From this segment upstream, the Corpus Christi terrace shows a steeper gradient than that at Corpus Christi, being 16 feet in 5.4 miles or 2.9 feet per mile toward the west, as against 10 feet in 6.6 miles east of the scarp, or 1.5 feet per mile toward the east.

There is not sufficient evidence in hand to determine whether the Angelita Terrace was offset by the faulting, as the single remnant of this terrace above sea in the portion of the valley in which the Corpus Christi Terrace is levelled is too short to yield a satisfactory determination of its slope. This terrace is cut by a 10-foot scarp at Angelita, suggesting that two terraces are involved or some type of local deformation. This Angelita Terrace seems to have had a pronounced cross-valley slope which renders interpretation difficult.

Relation of scarp to oil and gas production.—The present oil and gas production in the western part of the Saxet field is in scattered groups of wells which have not yet[17] revealed the limits of the producing area (Fig. 15). It has reached the east foot of the scarp. On the scarp are several "dry holes." West of it, the Bess *et al.* Boory gas well No. 1 seems to indicate a productive area whose size and outlines are unknown. As has been stated, no subsurface study of this newly drilled part of the field has been made for this paper.[18]

Along the Corpus Christi to Calallen and Nuecestown road, which follows the edge of the Nueces Valley, are three dry holes which seem, at present, to separate the oil-producing area of the main Saxet field from a group of four producing oil wells on McGregor land on the south edge of the Viola Terrace remnant. These wells lie along the trend of the Violet-Viola Scarp. If this scarp represented a single fault line without offsets, we would have expected the wells on the McGregor land to be dry, unless they are producing from sands on the local "high" west of the fault which stands above the edge water in the same sands west of the fault and southwest of the McGregor land.

On the basis that the scarp is a fault-line feature, we may assume, as a working hypothesis, that the Saxet field is a faulted nose, tilted up at its east end and lying level along its axis to the west end. The area west of the fault may be another tilted block, which has moved up on its east side. The dry holes on the scarp would be interpreted as marking northwest-flank water at the west end of the Saxet nose and water on the southeast flank of a "structural high" associated with oil and gas west of the fault. Similarly, dry holes along "Salt Creek" represent water-soaked sand downdip on the east end of the Saxet nose. Gas production in the shallow sands low on the flanks of this nose is probably controlled by the known lenticular condition of these sands in that area.

[17] June 15, 1933.

[18] As the manuscript goes to the publisher it is reported by the field superintendent of the Gulf Port and Karona operations that cores showing fault-plane sections were taken in a well on the fault scarp (see description of Figure 15).

Thus, there is some support for the belief that there are, south of Nueces River in the Saxet area, two productive fault blocks separated by the Violet-Viola fault: the Saxet block on the east, and the Boory block on the west.

If we follow the trend of the scarp across Nueces Valley, along the southeast meander scar of White Point Peninsula, we find the White Point productive structural nose, or structural dome, west of this meander scar; also a group of dry holes along it, with some wells which had gas pressure but very low volume; and, on the east, a group of wells on the Kirk land which are reliably reported to have shown strong gas in shallow sands before there was a pipe-line outlet for the area. There may, then, be pairs of fault blocks on each side of the valley separated by the Violet-Viola fault. Structural "lows" along the fault, at White Point, and near Viola in the Saxet area, may produce minor irregularities in the pattern of the oil and gas accumulations.

At the present stage of development, the suggestions advanced to explain the location of dry and productive wells can not be considered as proved.

Basis of interpretation of Violet-Viola-White Point Scarp as fault-line scarp.—Reasons for this interpretation are: the apparent offsets in the Beaumont Plain and Corpus Christi Terrace at the scarp; the disturbance of the gradient of the latter for 7 miles upstream; the coincidence between the topographic scarp on the Beaumont Plain and the apparent position of the east flank of the White Point structural nose; deflection of an ancient distributary at White Point in alignment with the fault, and the partial support lent to this interpretation by the distribution of productive areas of oil and gas, as so far shown by the drilling. Barton suggests that the scarp, if deformational, may be a flexure-scarp possibly overlying a fault.

Insufficient evidence for gulf-facing terrace at Violet.—If we attempt to apply the opposing hypothesis of marine terraces (Cooke, 1930a, 1930b, 1931) to the area and to include this scarp as one, we shall be unable to trace a definite scarp on the topographic maps southwestward from the vicinity of Violet across the Petronilla Quadrangle, either on or south of the Robstown-Laguna Larga ancient distributary ridge. The writer at first (Price, 1930a) attempted to apply the marine-terrace interpretation to this area, but was unable to select any set of scarps which would hold with the degree of continuity demanded of marine terraces, except in the case of that of the Ingleside Terrace at 12–20 feet above sea. The idea then advanced by the writer that Nueces Valley was embayed at the 25-, 50-, and 75-foot levels with the production of level flood plains to the western extremity of the area

will not hold after close study of the river terraces, and of the soil pattern.

The recognition of the Beaumont Terrace of Deussen as a typical deltaic plain in the Corpus Christi area shows that records of supposed Pleistocene fluctuations of sea-level in connection with fluctuations of continental ice sheets must be sought as records of contacts between sub-sea and sub-aerial portions of delta deposits, and as local beach scarps of bays, and not as relatively continuously preserved topographic scarps. Such contacts may be extremely difficult to discover because of (1) unequal compacting of delta sediments as sites of deposition shift (Trowbridge, 1930), (2) covering of early sub-sea delta deposits by later sub-aerial or delta-plain deposits, by which process old, marine, shore-line features may lie buried by later deposits, and (3) later planation of meandering distributary channels of the rivers.

Full discussion of this topic would go beyond the limits of the present paper, since the controversy over fault scarps *versus* marine terraces is of long standing in geology.

SUMMARY OF INTERPRETATION OF TOPOGRAPHIC EXPRESSION OF DIASTROPHIC STRUCTURES IN AREA

Normal topographic features preserving lines of deformational structure.—The coincidence of topographic features, or of parts of topographic features, with the strike of warped strata as determined by subsurface studies is striking in the two developed fields of the area. How much of this coincidence might have been guessed before development is uncertain. The point at which a given meander-scar cliff will leave the strike of the buried strata and continue down the valley in disregard of structural slopes is not predictable. A concentric or extensively linear alignment of slopes on topographic features of diverse origins seems to be the best evidence to be expected from topography of the presence of a large structure of diastrophic origin.

Inter-meander spurs of unequal value as oil and gas prospects?—The Saxet field itself is not outlined along more than one side by any single topographic feature. The White Point field, however, is bounded on two adjacent sides, as we now know the structure and the production in the shallow gas sands, by the scarps of an inter-meander spur.

Search for a similar relationship between a prominent inter-meander spur and a warped structure probably led to the drilling of Frank Allen's Giron well No. 1 at the southwest angle of the Calallen spur to a reported depth of 4,470 feet. A showing of oil is reported in this well. Drilling on and near a clay dune or terrace remnant at the east foot of this meander spur (Nueces River Bed Development Company's No.

1) has also been unsuccessful down to a depth of 3,935 feet. The White Point spur is, however, 2.3 times as large in area as the Calallen spur; hence, it is a much more prominent feature.

Scarps due to faulting or to flexure above fault.[19]—The fresh, opposing scarps of the Laura Thompson topographic graben are highly suggestive of a faulted graben. The writer has not studied this feature on the ground or in relation to regional topography and physiography, but there seems little doubt of its marking a faulted graben. On the topographic sheets showing the Corpus Christi area as herein defined there are not found fault scarps of this degree of freshness and supposed recency.

This topographic graben occurs between Medio Creek and Aransas River in Bee County near the Refugio County line, northwest of Woodsboro and in a direct line between Blanconia and Papalote. The scarps bear from N. 55°E. to N. 70°E., being aligned slightly convex toward the west. They face one another and appear to be intersected by the flood plains of the streams.

The interpretation of the Violet-Viola Scarp as a fault scarp whose cliff has been reduced by erosion to a more or less uniform slope similarly to the erosive flattening of the shore-line scarps of the Ingleside Terrace will probably not go unchallenged until such time as an adequate subsurface study shall have been made. The fault scarp is somewhat short for conclusive evidence and the number of river-terrace remnants is statistically small for complete proof of a disturbance of level not caused by normal stream erosion and deposition. The evidence for faulting is, therefore, somewhat circumstantial, but it furnishes the best explanation for the present pattern of the oil- and gas-producing areas in the two fields and allows the easing by faulting of a somewhat too greatly elongated structural nose which would be the result from the subsurface contours in the earlier developed, eastern part of the Saxet field if a fault is not introduced toward the west.

Barton's suggestion that the sloping Violet-Viola topographic scarp, if of diastrophic origin, may be a flexure scarp possibly overlying a fault, is to be taken into consideration. The question of whether this scarp should be considered a *fault scarp* or a *fault-line scarp* (one recessed by erosion from its original position) is a question of how soon, in the erosive history of the fault scarp, it is to be termed a fault-line scarp. The present scarp has probably not receded wholly from its original position and may have suffered equal erosion with the scarps of the Ingleside Terrace basins whose tops have weathered back in places as much as a mile.

[19] See report of fault plane showing in cores along scarp, in description of Figure 15.

Negative evidence from physiography not yet proved adequate to condemn territory for oil or gas in area.—With so few areas in South Texas covered by detailed topography, either on the Coast Prairie or inland, it seems premature to assume that all or most of the oil and gas fields to be found either may or may not have some sort of topographic expression.

Though it is a fact that the two present fields of the Corpus Christi area have topographic expression, as have also several of those of inland areas, some salt domes of the Houston-New Orleans region suggest that there may be, in the Corpus Christi area, diastrophic structures which have had no movements recent enough to be reflected in Pleistocene and Recent deposits, and hence in the topography.

If it be suspected that a certain area is underlain by a structure of diastrophic origin, the fact that all the overlying topographic features have simple physiographic explanations should not condemn it as an oil and gas prospect, since we should study the relative arrangement of these features, rather than their origins alone.

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A. C. Veatch (1906), "Geology and Underground Water Resources of Northern Louisiana and Southern Arkansas," *U. S. Geol. Survey Prof. Paper 46*. 422 pp.; map.

J. Versluys (1931), "Subterranean Water Conditions in the Coastal Regions of the Netherlands," *Econ. Geol.*, Vol. 26, No. 1 (January–February), pp. 65–95, Figs. 1–11.

[21] George Castor Martin, archaeologist. "Callo" is properly Cala (Spanish, *bay*), referring to the embayed mouth of Oso Creek.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
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PARADOX FORMATION OF EASTERN UTAH AND WESTERN COLORADO[1]

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Washington, D. C.

ABSTRACT

The Paradox formation consists of gypsum, anhydrite, and salt, interbedded with shale, sandstone, and limestone. It is the oldest rock exposed in several anticlines in eastern Utah and western Colorado and has been found in a number of wells in the same region. The occurrences indicate much movement of materials, apparently due to the relatively plastic character of salt deposits, and the relationships and true thickness are difficult to determine. Actual thickness in wells exceeds 6,000 feet, but the maximum original thickness may not have been more than about 2,000 feet. The Paradox formation is believed to be conformable with the overlying Hermosa formation and unconformable on the underlying Mississippian beds, though normal contacts have not been observed. The formation contains a few fossil plants, invertebrates, and conodonts which agree in indicating a lower Pennsylvanian age, though the writers infer that the Paradox is wholly older than the Hermosa formation. It is suggested that the Paradox formation occupies an elongated basin southwest of the Uncompahgre uplift and that it thins out southward at Elk Ridge, Utah; westward at San Rafael Swell, Utah; eastward at the Uncompahgre uplift. It is also suggested that the saliferous beds constituting the "Weber shales" northeast of the Uncompahgre uplift occupy another basin essentially contemporaneous with that occupied by the Paradox formation, though perhaps not connected with it.

INTRODUCTION

During the course of detailed mapping in southeastern Utah and reconnaissance studies in western Colorado, the writers have had to deal with a gypsiferous series of beds whose stratigraphic relations and age, owing to unusual structural conditions and the scarcity of organic remains, have long remained uncertain. These particular beds, which have been named the Paradox formation, have attracted some attention in recent years because they have yielded showings of oil and gas in several wells and evidence of a notable amount of saline rocks, including some potash-bearing minerals.

Discussions of the Paradox formation in certain restricted regions in Utah are to appear in reports by Baker[3] and Dane,[4] but in the pres-

[1] Read before the Association at the Houston meeting, March 25, 1933. Manuscript received, April 28, 1933. Published by permission of the director of the United States Geological Survey.

[2] United States Geological Survey.

[3] A. A. Baker, "Geology and Oil Possibilities of the Moab District, Grand and San Juan Counties, Utah," *U. S. Geol. Survey Bull. 841* (1933).

[4] C. H. Dane, "Geology of the Salt Valley Anticline and the Northwest Flank of the Uncompahgre Plateau, Grand County, Utah," *U. S. Geol. Survey Bull.* (in preparation).

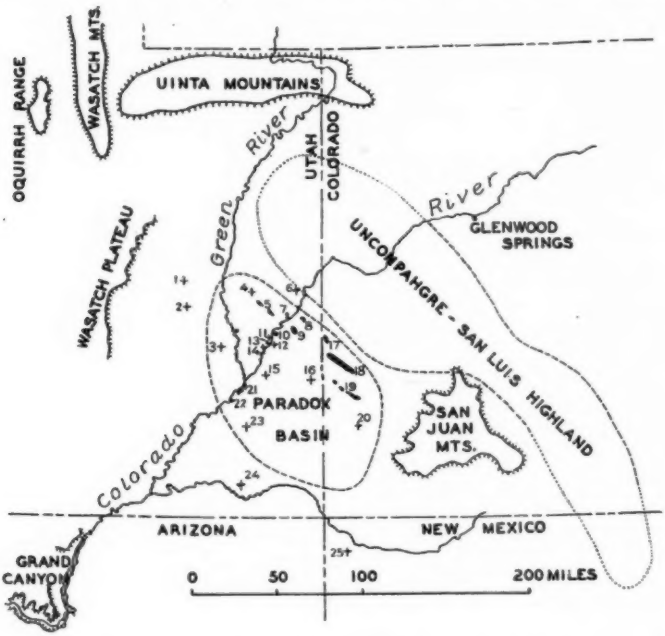

FIG. 1.—Map showing inferred limits of Paradox basin.

EXPLANATION OF LOCALITY NUMBERS

1. Black Box Canyon of the San Rafael River.
2. Straight Wash
3. Phillips Petroleum Company's well
4. Crescent Eagle Oil Company's well
5. Outcrops of Paradox formation in Salt Valley
6. Utah Southern Oil Company's State well No. 1
7. Outcrops of Paradox formation in Cache Valley
8. Outcrops of Paradox formation in Onion Creek
9. Outcrops of Paradox formation in valley of Castle Creek
10. Outcrops of Paradox formation in Moab Valley
11. Midwest Refining Company's J. L. Shafer well No. 1-A
12. Snowden and McSweeney's Prommel well No. 1
13. Midwest Refining Company's Frank Shafer well No. 1
14. Midwest Refining Company's J. H. Shafer well No. 1
15. Empire Gas and Fuel Company's well
16. Union Oil Company's well in Lisbon Valley
17. Outcrops of Paradox formation in Sinbad Valley
18. Outcrops of Paradox formation in Paradox Valley
19. Outcrops of Paradox formation in Gypsum Valley
20. Transcontinental and Ohio Oil Company's well
21. Outcrops of Paradox formation in the Canyon of Colorado River
22. Outcrop of Paradox formation in Gypsum Canyon
23. Midwest Refining Company's Elk Ridge well
24. Utah Southern Oil Company's Cedar Mesa well
25. Continental Oil Company's wells in the Rattlesnake field

ent paper the information acquired by these authors in the areas of detailed work is presented, together with information derived from reconnaissance observations in other areas and the data yielded by a number of widely spaced deep wells. This paper describes the formation as a stratigraphic unit and does not discuss extensively the peculiar structural features with which it is associated.

GENERAL FEATURES OF PARADOX FORMATION

Definition and distribution.—The Paradox formation is named from the exposures along the floor of Paradox Valley, Montrose County, Colorado, particularly those near the town of Paradox. It is typically a series of beds of gypsum, anhydrite, salt, black shale, fine-grained sandstone, and gray limestone. It underlies the Hermosa formation of southeastern Utah, principally in Grand and San Juan counties, and of western Colorado west of the Uncompahgre Plateau principally in Mesa, Montrose, and San Miguel counties. The base of the formation is not ordinarily exposed.

The accompanying sketch map (Fig. 1) shows the location and areal extent of the known exposures of the formation.

Nature of outcrop.—The Paradox formation is exposed only along the crests of a few anticlinal folds and at the apex of a few small steep-sided domes, these outcrops being separated by wide expanses of younger beds. It has been involved in several periods of earth movements, and because some of its beds are composed of relatively plastic constituents, it has been folded more complexly and brecciated more than the enclosing rocks. At places the movements of the material in the Paradox formation have ruptured the roofs of folds and the materials of the formation have moved upward from their normal position and have come into contact with much younger beds. The resulting masses are much disturbed and broken, and it is difficult to determine their thicknesses and true stratigraphic relationships.

Difficulty of securing precise data.—As noted, the Paradox formation crops out in small areas that are separated by wide areas where it is covered by younger formations, and, in addition, the relatively plastic saliferous beds have obviously been much disturbed by flowage. The data obtained at the outcrops must therefore be supplemented by those obtained from deep wells. As most of these wells have been drilled with cable tools and few cores have been taken, only the drillers' descriptions of the rocks cut by the drill have been available to the writers and it is possible that the data so recorded are imperfect. For example, some saliferous beds, particularly anhydrite beds, may well have been recorded as limestone by the drillers. Although such

imperfect subsurface information, when coördinated with information obtained at the outcrops, permits inferences to be drawn, the conclusions reached can not be regarded as final.

PREVIOUS STUDIES

The first brief description of beds forming part of the Paradox formation was given by Peale in 1875.[5] He observed the gypsum, shale, and limestone exposures on the floor of Sinbad Valley in western Colorado (locality 17, Fig. 1) and regarded them as Permian or "Permo-Carboniferous" in age, because he believed, erroneously, that they conformably overlay eastward dipping *Productus*-bearing limestones on the west side of the valley and dipped eastward conformably beneath the conglomeratic red beds exposed on the east side of the valley.

In 1907 Cross[6] recorded the presence of a considerable thickness of gypsiferous beds "in the valley of Fisher Creek" (along Onion Creek; locality 8, Fig. 1) and recognized their probable equivalence to the gypsiferous beds of Sinbad Valley, but remarked that a zone of faulting and folding like that in Sinbad Valley hindered an accurate determination of relationship.

In 1921 Coffin[7] described the exposures of the Paradox formation in Sinbad, Paradox, and Gypsum valleys in western Colorado. He included in one unit all exposed sedimentary rocks stratigraphically below the Permian Cutler formation and termed them the "gypsum series." He recognized that equivalents of the Hermosa formation of the San Juan Mountains were present in a few places and that these fossiliferous limestone beds and associated sandstones and conglomerates were at least in part stratigraphically above the gypsum beds. He accepted Peale's early belief that the gypsum beds of Sinbad Valley conformably overlie the "*Productus*-bearing limestones" of the west side, though these limestones are quite surely part of the Hermosa formation and are above the Paradox formation. Cross,[8] however, had already stated that

> the fault zone parallel to the axis of the valley is more complex than Peale supposed and it seems probable that the fossil-bearing strata form a narrow and vertically upturned block . . . . . and that no continuous

[5] A. C. Peale, "Geological Report on the Grand River District," *U. S. Geol. and Geog. Survey Terr. Ninth Ann. Rept.* (1875), pp. 71–77.

[6] Whitman Cross, "Stratigraphic Results of a Reconnaissance in Western Colorado and Eastern Utah," *Jour. Geology*, Vol. 15 (1907), p. 666.

[7] R. C. Coffin, "Radium, Uranium, and Vanadium Deposits of Southwestern Colorado," *Colorado Geol. Survey Bull. 16* (1921), pp. 36–45.

[8] Whitman Cross, *op. cit.*, p. 671.

section exists in the valley by which the position of these fossiliferous beds in the whole section can be established.

The evidence accepted by Coffin was thus somewhat conflicting. He reached the conclusion that the gypsum series was part of the Hermosa formation.

In 1927 Harrison[9] discussed the same region and also the adjoining area in southeastern Utah, and regarded the gypsum, shale, and salt beds as "lower Hermosan." In the same year Prommel and Crum[10] recognized the gypsum, shale, and salt series as underlying the Hermosa limestone of the eastern Utah region, but assigned no age to the series. In a slightly later paper[11] they separate the "dark shale, gypsum anhydrite, salt" from the Hermosa formation and remark that it is a saline facies of lower Pennsylvanian or older formations. In a paper[12] contemporaneous with this later paper, the opinion is expressed by Baker and others that the Hermosa age of the shale, salt, and gypsum beds below the limestone is not yet established.

LITHOLOGIC FEATURES

Features in outcrops.—The exposures of the Paradox formation at most localities are predominantly of gypsum, which in many places includes small broken chunks of gray limestone, sandstone, and black shale. Two exceptions are the outcrops in the valley of Onion Creek (Fig. 1, locality 8), and in Sinbad Valley (Fig. 1, locality 17). In these the most abundant rock type is thin-bedded black shale, in units several feet thick or in thin beds alternating with very fine-grained gray sandstone. There are also gray sandy shales. These and the sandstone locally contain lignitic fragments and at places are very carbonaceous. The bedding is for the most part thin and regular and all bedding surfaces observed are flat, without ripple bedding. Dense gray limestone and sandy limestone are common. Much of the shale and sandy shale is somewhat gypsiferous and salty. Gypsum in thick beds is abundant. Dark reddish brown highly resinous beds have been observed by the

[9] T. S. Harrison, "Colorado-Utah Salt Domes," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 11, No. 2 (February, 1927), pp. 111–33.

[10] H. W. C. Prommel and H. E. Crum, "Salt Domes of Permian and Pennsylvanian Age in Southeastern Utah and Their Influence on Oil Accumulation," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 11, No. 4 (April, 1927), pp. 373–93.

[11] H. W. C. Prommel and H. E. Crum, "Structural History of Parts of Southeastern Utah from Interpretation of Geologic Sections," *Bull. Amer. Assoc. Petrol. Geol.* Vol. 11, No. 8 (August, 1927), pp. 809–20.

[12] A. A. Baker, C. E. Dobbin, E. T. McKnight, and J. B. Reeside, Jr., "Stratigraphy of the Moab Region, Utah," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 11, No. 8 (August, 1927), pp. 786–808.

writers, and Harrison[13] records petroliferous shales and limestones and pieces of a hydrocarbon, possibly gilsonite, from the Onion Creek area. In thin section the sandstones of the formation show small and extraordinarily angular grains of quartz, sodic plagioclase, and microcline in a matrix of carbonate and clay minerals. The largest grains are as much as $\frac{1}{4}$ millimeter (.01 inch) in longest dimension, but are mostly about $\frac{1}{10}$ millimeter (.004 inch) in size. There are abundant flakes of biotite and some flakes of chlorite. Bright green rounded grains of glauconite are common.

Features in wells.—Wells drilled into the formation report great thicknesses of salt in beds alternating with anhydrite, shale, and limestone. Bedded potash salts have also been penetrated. The accompanying record of the J. H. Shafer well No. 1 in Sec. 16, T. 27 S., R. 20 W., Utah (Fig. 1, locality 14) is illustrative of the lithology of the Paradox and the overlying Hermosa formation as reported from numerous wells that have been drilled into them. The lithologic descriptions are as reported by the driller, but the interpretation of the formation boundaries has been made by the writers.

THICKNESS

The rocks of the Paradox formation at all known exposures are so folded, faulted, and brecciated that the continuity of bedding planes is destroyed and it is not possible to measure a complete section in outcrop. The only possible chance of determining the thickness is from the logs of wells that may have been drilled through the formation. A complete section is probably not present in most of the deep wells drilled in the region. However, the J. H. Shafer well No. 1 (Fig. 1, locality 14) south of Moab, Utah, the log of which is shown on an accompanying page, is believed by the writers to have been drilled through the formation in the area of its greatest development, and its log therefore might be usable in determining thickness.

This well passed through a zone more than 3,900 feet thick containing much salt and gypsum. Below the zone containing the salt and gypsum the well penetrated 293 feet of limestone and shale to the bottom of the well. The lower 173 feet of this interval is variegated shale containing fresh water, and as it seems unlikely that a water-bearing bed inclosed in salt-bearing beds would carry fresh water, it appears probable that this shale formation actually underlies the saliferous Paradox formation and is not part of it. The thickness for the Paradox formation of about 4,100 feet thus obtained in this well is, however, probably not the normal thickness of the formation, nor can great

[13] T. S. Harrison, *op. cit.*, p. 117.

RECORD OF THE J. H. SHAFER WELL NO. 1 IN SEC. 16, T. 27 S., R. 20 E., UTAH

HERMOSA FORMATION	*Depth in feet*
Blue limestone	25
Red sandstone, water-bearing	63
Limestone	73
Sandstone, water-bearing	81
Red shale	100
Hard brown limestone	110
Blue shale and hard shell	131
Gray limestone	145
Shale	208
Gray limestone	282
Shale	285
Gray limestone	350
Black slate	365
Black limestone	375
Gray limestone	414
Black shaly limestone	425
Gray sandy limestone	440
Muddy sandstone	465
Limestone	485
Dark sandstone	495
Sandy brown shale	525
Gray limestone	570
Brown shale	590
Brown limestone	596
Gray shale	599
Brown limestone	605
Interbedded shale and limestone	626
Gray limestone	655
Blue shale	660
Gray limestone	670
Blue shale	680
Sandstone	685
Gray limestone	696
Gray shale	701
Gray limestone	718
Sandstone	724
Gray limestone	753
Blue shale	764
Sandstone	782
Gray shale	784
Gray limestone	833
Gray shale	840
Gray limestone	880
Gray limy shale	925
Gray limestone	929
Gray shale	955
Gray limestone	1,105
Black limestone	1,175
Black shale	1,180
Gray limestone	1,186
Gray shale	1,290
Gray limestone	1,309
Gray sandy shale	1,320
Gray limestone	1,333
Black limestone	1,362
Gray limestone	1,483
Shaly limestone	1,487
Gray limestone	1,500
Limy shale	1,525
Black limestone	1,544
Black shale	1,550
Black limestone	1,565
Gray limestone	1,610

PARADOX FORMATION	*Depth in feet*
Limestone and salt	1,620
Salt	1,633
Shell	1,635
Salt	1,735
Limestone	1,745
Brown sandstone	1,755
Black slate	1,770
Black shale	1,788
Black limestone	1,796
Salt	1,800
Limestone and salt	1,820
Limestone	1,823
Salt	1,899
Gray limestone	1,938
Black shale	2,040
Salt	2,050
Limestone	2,075
Gray shale	2,094
Limestone	2,100
Sandstone, shale, and salt	2,125
Salt	2,255
Limestone	2,270
Gray shale	2,365
Salt	2,383
Gray shale	2,490
Salt	2,590
Shale and gypsum	2,600
Salt	2,790
Shale and gypsum	2,825
Salt	2,990
Limestone	3,040
Salt	3,240
Sandy shale	3,270
Black shale	3,305
Salt	3,348
Gray shale and gypsum	3,410
Salt	3,540
Gray shale	3,595
Salt	3,660
Gray shale	3,696
Salt	3,960
Black shale	3,965
Salt	4,325
Gray shale and gypsum	4,380
Salt	4,856
Brown shale	4,897
Gray shale and gypsum	5,015
Salt	5,280
Black shale	5,320
Gray sandy shale	5,390
Salt	5,515
Black shale and gypsum	5,570
Gray sandy shale	5,590
Black limestone	5,615
Gray sandy shale	5,680
Limestone	5,690
ROCKS OF PRE-PARADOX AGE (?)	
Variegated shale, fresh water	5,863
Bottom of well	5,863

weight be given to the incomplete thicknesses obtained in other wells, as much as 6,000 feet in Paradox Valley, for example. All of these wells have been drilled near the crests of anticlines, and if the reasonable assumption is made that the salt has been thickened at the crests of the anticlines by lateral flowage into them, any figure obtained for thickness is excessive and would need to be reduced to approximate the original, normal thickness. It is probably safe to assume that the maximum normal thickness of the formation exceeds 2,000 feet.

STRATIGRAPHIC RELATIONS

Contact with older rocks.—Little is known directly concerning the rocks which underlie the Paradox formation, and it is necessary to draw some information from stratigraphic successions in adjoining regions. In the San Juan Mountains of Colorado, the Hermosa rests upon the thin Molas formation. The Molas contains conglomerate beds, in which are pebbles containing lower Mississippian fossils, but a scanty invertebrate fauna has been found in the Molas itself which indicates its Pennsylvanian age and which has some points of similarity with the fauna of the overlying Hermosa formation. The Molas rests upon an erosional unconformity cut on the underlying Leadville limestone (upper part of the Ouray limestone of most older reports) which is of lower Mississippian age.[14]

The only outcrop evidence of rocks that may underlie the Paradox formation is given by two exposures of conglomerate in the north end of Salt Valley, Utah. One of these is in Section 15 and the other in Sections 9 and 10, T. 23 S., R. 20 E. This conglomerate contains boulders of limestone and chert as much as 15 inches in diameter, embedded in a yellow sandstone matrix. The boulders contain fossils, all of which are regarded by G. H. Girty as either Mississippian in age or longer-ranging species that could be Mississippian.[15] Because of the similarity in lithology to the basal Pennsylvanian Molas formation it seems probable that this conglomerate is of early Pennsylvanian age and analogous in its stratigraphic position to the Molas formation of the San Juan Mountains. Probably, also, it originally rested on a Mississippian limestone analogous to the Leadville and Madison limestones. The stratigraphic relations of the conglomerate have not been ascertained directly, however, because of complicated structure and incomplete exposures. Nor are the outcrops of conglomerate

[14] Whitman Cross and Others, *U. S. Geol. Survey Geol. Atlas, Silverton Folio 120* (1905), p. 4. Edwin Kirk, "The Devonian of Colorado," *Amer. Jour. Sci.*, 5th ser., Vol. 22 (1931), pp. 226–27.

[15] A. A. Baker and Others, *op. cit.*, pp. 789–90. C. H. Dane, *op. cit.*

known to be directly underlain in their present position by Mississippian limestones, for they may represent isolated blocks of the underlying floor torn up and carried upward within the beds of the Paradox during flowage of the plastic saliferous beds.

Contact with younger rocks.—The nature of the contact between the Paradox formation and the Hermosa formation is not definitely known, for the Paradox may have moved from its original stratigraphic position even at the few localities where it is in contact with Hermosa beds on the outcrop. Well records indicate some alternation of Hermosa and Paradox lithology across a transition zone, but there is no assurance that this alternation is an original stratigraphic feature rather than some subsequent rearrangement due to invasion of the Hermosa formation by more plastic constituents of the Paradox. It seems likely that the contact between the two formations is a conformable one, however, probably with a transition zone intervening between them but with, on the whole, a moderately sharp change in lithology.

Fossils and age.—The first fossils reported from the Paradox formation were conodonts that were noted by geologists of the Midwest Refining Company in cuttings of dark shale at the Frank Shafer well No. 1 (Fig. 1, locality 13). This well is in the SW.$\frac{1}{4}$, Sec. 31, T. 26 S., R. 21 E., on Cane Creek anticline, about 9 miles southwest of Moab, Utah. This dark shale zone in this well (depth 3,250 to 3,350 feet) is overlain and underlain by a considerable thickness of salt. P. V. Roundy has examined the cuttings and has made the following report.

All cuttings are of a fine-grained black shale. Eight of the samples contained conodonts while two (3,270–3,280 and 3,340–3,350) contained no fossils. The cuttings from 3,320–3,330 contained 44 specimens. In all, 105 specimens were picked out; all were incomplete, but seven genera were recognized.

Of these, two genera, *Hindeodella* and *Lonchodus*, range from Devonian to lower Permian. The species of *Hindeodella*, however, is distinct from the Devonian type. As the anterior ends of all specimens were missing, a specific identification is not possible. *Lonchodus* is an indeterminate genus and has no stratigraphic value.

The Carboniferous genus *Gnathodus* is represented and the type in these cuttings ranges, so far as I know, from middle or upper part of lower Mississippian to upper Pennsylvanian. It is, however, I believe, a Pennsylvanian rather than a Mississippian species.

Another genus, undescribed, but nearer to *Gnathodus* than *Polygnathus*, occurs only, so far as I know, in the Pennsylvanian and Permian. The two species of this form are very abundant in the cuttings and I believe they are probably the Pennsylvanian type.

The other three genera are represented only by such imperfect specimens that their identification is not at all sure, but they do not forbid a reference of the cuttings to the Pennsylvanian.

The conodont evidence indicates that the shale from 3,250 to 3,340 feet in the well is a single unit and that in age it probably belongs in the lower half of the Pennsylvanian. It can not be Devonian and probably is not Mississippian unless these conodonts range lower than present knowledge would indicate. However, if other information supports a reference to the upper Pennsylvanian the conodont evidence would offer but little objection to such a position.

In September, 1929, H. D. Miser and the writers collected an invertebrate fauna from black shale of the Paradox formation at a locality about 1 mile west of the point where Salt Wash leaves Sinbad Valley, Mesa County, Colorado. The following fossils were identified by G. H. Girty.

Conularia crustula
Orbiculoidea sp.
Chonetes sp.
Ambocoelia planiconvexa
Nucula sp.
Leda aff. *arata*
Schizodus sp.
Deltopecten aff. *arkansanus*
Euchondria neglecta?
Clinopistha radiata var. *Levis?*
Phanerotrema aff. *grayvillense*
Trepospira sphaerulata
Pleurotomaria? sp.

Concerning this collection, Girty says in part:

I am satisfied that the age of these beds is Pennsylvanian. The fauna probably represents some horizon in the Hermosa formation, though nothing closely resembling it is as yet known from the typical Hermosa. It might represent some pre-Hermosa formation that has not as yet been distinguished though it is unlike the very scanty fauna of the Molas formation at present known.

H. D. Miser and the writers collected also some fragmentary plant fossils from gray sandy shales of the Paradox formation cropping out just south of the place where Salt Wash leaves Sinbad Valley. This material was submitted to David White of the United States Geological Survey for examination. He determined that the plant material, although unsatisfactory, indicated strongly that the beds were Pennsylvanian in age and probably of early Pennsylvanian age.

The evidence now available from fossil plants, invertebrates, and conodonts, though somewhat meager, thus agrees within itself in indicating a lower Pennsylvanian age for the Paradox formation. The writers interpret the conglomerate containing reworked Mississippian material and found in Salt Valley to be a Pennsylvanian unit derived in part from Mississippian rocks and in no way to militate against the assignment of the formation to the Pennsylvanian.

POSSIBLE EQUIVALENCE OF PARADOX FORMATION AND LOWER PART OF HERMOSA FORMATION

The suggestion has been made by several authors that the beds now called the Paradox formation are equivalent to the lower part of the

Hermosa of the San Juan Mountains, and the occurrence of bedded gypsum in the lower Hermosa of the Rico Mountains[16] has been cited as evidence for this correlation.

The lower Hermosa of the Rico Mountains is poorly exposed, but is known to include beds of black shale, green or gray grits or sandstones, gray shales, and thin impure limestones.[17] A bed of gypsum reaching in some places a thickness of 30 feet occurs locally above black shales near the base. Although these beds are lithologically not unlike the Paradox beds, some of the limestones and shales differ in that they contain abundant fossils, thus contrasting with the uniformly unfossiliferous limestones of the Paradox formation.

Farther southeast, in the Animas Valley, the lowest third of the Hermosa is made up of green sandstones and shales with some gypsiferous shales, and the rest of the formation shows limestone layers distributed throughout. The basal stratum of the formation is a notably persistent, massive limestone, containing abundant fossil shells.[18] The shales and impure limestones with identifiable fossils which occur at the base of the Hermosa in the Rico district are regarded as corresponding with similar strata in the Animas Valley.[19]

The Hermosa as exposed in the Ouray district contains a larger proportion of coarser clastics than at Rico or in the Animas Valley, thus reflecting a closer approach to the source of the sediments in the Uncompahgre Highland to the north. A lower division 450 feet thick is, however, recognized by Burbank, which consists predominantly of thin alternating beds of sandstone, shale, and thin fossiliferous limestone with a few layers of conglomerate. There are a few thin dense limestone beds near the base, interbedded with black carbonaceous shales. Many of these limestones and shales are fossil-bearing. The sandstones are prevailingly gray or greenish in color, but some of the coarser grits are pinkish. The shales are prevailingly dark, but some are greenish or reddish.[20]

In a deep well (Fig. 1, locality 20) drilled by the Transcontinental

[16] Whitman Cross and F. L. Ransome, *U. S. Geol. Survey Geol. Atlas, Rico Folio 130* (1905), p. 3.

[17] Whitman Cross and A. C. Spencer, "Geology of the Rico Mountains, Colorado," *U. S. Geol. Survey 21st Ann. Rept.*, Pt. 2 (1900), pp. 50–53.

[18] Whitman Cross, *U. S. Geol. Survey Geol. Atlas, Engineer Mountain Folio 171* (1910), p. 6. Whitman Cross, Ernest Howe, and J. D. Irving, *U. S. Geol. Survey Geol. Atlas, Ouray Folio 153* (1907), p. 4.

[19] Whitman Cross and F. L. Ransome, *U. S. Geol. Survey Geol. Atlas, Rico Folio 130* (1905), p. 3.

[20] W. S. Burbank, "Revision of Geologic Structure and Stratigraphy in the Ouray District of Colorado, and Its Bearing on Ore Deposition," *Colorado Sci. Soc. Proc.*, Vol. 13, No. 6 (1930), pp. 163, 164.

and Ohio oil companies, in Sec. 30, T. 41 N., R. 16 W., in Dolores County, Colorado, about 30 miles west of the Rico district, a series of beds logged chiefly as salt was found from a depth of 6,060 feet to 6,625 feet. These beds, which are correlated by the writers with the Paradox formation, underlie limestones of Hermosa type and this locality is the southeasternmost locality at which strata definitely correlated with the Paradox formation are known. Beneath the salt beds the well passed through 139 feet of gray limestone and sandy limestone, which may be of Mississippian age.

Limited information indicates that the thickness of the Hermosa in its usual facies is fairly uniform across the area underlain by the Paradox formation and is comparable with the thickness of the formation in its typical area, the San Juan Mountains of Colorado. The great thickness of the Paradox formation beneath the Hermosa in Utah, therefore, strongly suggests that the Paradox antedates the lower Hermosa. As noted, a conglomerate like the Molas and possibly equivalent to it is present in Salt Valley either as detached blocks within the Paradox formation or as the underlying formation. The Paradox formation appears, therefore, to be somewhat younger than the Molas of the San Juan Mountains. The Paradox thus might either fall into an interval between the Molas and the Hermosa, or be contemporaneous with the lower part of the Hermosa. It seems to the writers a more satisfactory interpretation to consider the Paradox as a distinct formation which is older than the typical Hermosa of the San Juan Mountains.

PALEOGEOGRAPHIC RELATIONS ALONG WESTERN SIDE OF UNCOMPAHGRE UPLIFT

Extent of formation.—The paleogeographic relationships, which are evident from the stratigraphic features of the Hermosa and overlying Carboniferous and Lower Triassic formations, make it clear that during Pennsylvanian, Permian, and part of Triassic time a land mass extended northwestward through western Colorado.[21] The name San Luis Mountains has been applied to this highland by Melton.[22] It has also been called the Uncompahgre-Sangre de Cristo element by Ver Wiebe.[23] The southwestern margin of this land, here designated by

[21] C. H. Dane, "Uncompahgre Plateau and Related Structural Features (abstract), *Wash. Acad. Sci. Jour.*, Vol. 21, No. 2 (1931), p. 28. T. S. Lovering, "Geologic History of the Front Range, Colorado," *Colo. Sci. Soc. Proc.*, Vol. 12, No. 4 (1929), p. 81.

[22] F. A. Melton, "The Ancestral Rocky Mountains of Colorado and New Mexico," *Jour. Geology*, Vol. 33, No. 1 (1925), pp. 84–89.

[23] W. A. Ver Wiebe, "Ancestral Rocky Mountains," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 14, No. 6 (June, 1930), p. 770.

the authors as the Uncompahgre-San Luis highland, lay north of the present San Juan Mountains and had a northwest trend approximately coinciding with the western boundary of the present Uncompahgre Plateau. During Hermosa time coarse debris was discharged toward the southwest from this land into marine waters, and coarse conglomerates of little altered fragments of plutonic rocks accumulated alternately with marine fossiliferous limestones. There was a gradual change from this type of deposition through the interbedded marine and continental sediments of the Permian Rico formation to the apparently continental conglomeratic sediments of the Permian Cutler formation. Coarse debris from the land mass continued to be shed southwestward through Cutler time and also through the earlier part of the Triassic.

There is no evidence that this land mass was in existence during lower Mississippian time, for the known distribution and nature of the Leadville and equivalent limestones appear to indicate that they were continuous across the area later occupied by land. Sediments of upper Mississippian age are not known in western Colorado or eastern Utah, but the earliest Pennsylvanian, the Molas formation, reflects by its conglomeratic character the intervention of a period of erosion during which fossiliferous lower Mississippian chert boulders were formed and incorporated in the earliest Pennsylvanian sediments. The writers believe that the Molas formation and the sediments of the Paradox record the early gradual uprising of the Uncompahgre-San Luis highland. The Paradox sandstones, with their extraordinarily angular small grains, imply a short distance of transportation from their source, and the local preservation of abundant and delicate plant material points to the same conclusion. It seems probable that the lithologic constitution of the Paradox is partly due to the accumulation of the débris eroded from Mississippian, Devonian, and Cambrian sediments which rested on the pre-Cambrian core of the rising land. When these early Paleozoic sediments had been stripped, the still rising land contributed coarser and coarser clastics derived almost entirely from the rapid disintegration of the uplifted granitic and metamorphic pre-Cambrian rocks. This picture of the geologic events agrees with the theory that much of the Paradox antedates the Hermosa of the San Juan Mountains.

COMPARISON OF SEQUENCE IN WESTERN COLORADO WITH THAT IN WEST-CENTRAL COLORADO

The Paradox-Hermosa-Rico-Cutler sequence deposited on the southwest side of the Uncompahgre-San Luis highland is analogous

to the Weber(?)-Maroon[24] sequence on the northeast side of the land. The "Weber shales" are much like those of the Paradox formation and the exposures in the vicinity of Glenwood Springs and along Colorado and Eagle rivers above Glenwood Springs include thick contorted beds of gypsum and are lithologically identical with those of the Paradox formation west of the Uncompahgre Plateau. The "Weber shales" rest on Mississippian limestone and are succeeded upward by the "Weber grits," in places by gradation, but in others with a sharp separation between the two types of lithology. The "Weber grits" consist of interbedded micaceous gray grits and conglomerates and gray and black shales. The "Weber grits" are not sharply separable from the overlying Maroon formation, of Permian age. The Uncompahgre highland separating these two analogous sequences extended an unknown distance northwestward, where the record is concealed by the younger sediments of the Uinta Basin. From the region of the Uinta Mountains, little detailed information is available. On Vermilion Creek the Pennsylvanian rocks include 525 feet of gray hackly limestone, gray and red sandstone, gray shale, carbonaceous shale, and thin irregular beds of coal. These rocks are overlain by Weber quartzite, believed also to be Pennsylvanian, and this in turn by the Park City formation, believed to contain Pennsylvanian and Permian rocks.[25]

LIMITS OF PARADOX FORMATION

The stratigraphic relationships at the western and southwestern limits of the Paradox formation are not definitely known because of the widespread cover of younger formations. Evidence obtained from four wells in a series extending southward from the vicinity of Moab shows a decrease in the percentage of saliferous beds. In the Elk Ridge well (Fig. 1, locality 23) about 3,500 feet of limestone was found and only four thin beds of salt intercalated with considerable black shale were recognized. The beds of salt are immediately below the portion of the limestone that is somewhat arbitrarily correlated with the Hermosa formation and are underlain by about 1,700 feet of beds composed principally of limestone and barren of saliferous beds or black shale. The presence of about 250 feet of variegated shale with some intercalated limestone and sandstone at the base of the lower limestone unit in the Elk Ridge well suggests a correlation with beds of similar lithology and thickness found at the base of the Paradox

[24] T. S. Lovering, "Geologic History of the Front Range, Colorado," *Colo. Sci. Soc. Proc.*, Vol. 12, No. 4 (1929), p. 81.

[25] J. D. Sears, "Geology and Oil and Gas Prospects of Part of Moffat County, Colorado, and Southern Sweetwater County, Wyoming," *U. S. Geol. Survey Bull. 751* (1925), p. 283.

formation in the J. H. Shafer well No. 1 (Fig. 1, locality 14), which would in turn suggest the contemporaneity of the Paradox formation at the J. H. Shafer well No. 1 with the saliferous beds plus the lower limestone at the Elk Ridge well. It seems more probable, however, that part or all of the lower limestone series at the Elk Ridge well is of pre-Paradox age and served as the basement rock against which the Paradox formation overlaps. Still farther south, at the Cedar Mesa well (Fig. 1, locality 24), an almost unbroken series of limestone beds with only one thin bed of black shale was found to rest upon pre-Cambrian schist. The lower part of this limestone series is probably equivalent to the part of the limestone below the salt beds at Elk Ridge. If the driller's description of the rocks penetrated by these wells is accurate, there is obviously a limit to the saliferous beds somewhere between these two wells.

Southwest of Moab, three small domelike masses of gypsum crop out in the bottom of the Canyon of Colorado River a few miles below the mouth of Green River (Fig. 1, locality 21), and a fourth outcrop is reported still farther south in Gypsum Canyon[26] (Fig. 1, locality 22). Beyond Gypsum Canyon the Paleozoic formations dip below river level in a short distance, but they reappear in the vicinity of Grand Canyon, Arizona. Near Grand Canyon station, all rocks of Pennsylvanian age are absent and the Supai formation, of Permian age, rests on the Redwall limestone, of Mississippian age.[27]

West of Green River the Phillips Petroleum Company's well (Fig. 1, locality 3), in the Green River desert and two isolated outcrops in the San Rafael Swell supply the only evidence of the western limit of the saliferous beds. At the Phillips Petroleum Company's well, about 1,500 feet of beds composed principally of limestone lie between the Cedar Mesa sandstone, of Permian age, and a zone of anhydrite-bearing beds about 700 feet thick. The anhydrite-bearing beds rest on a cream-colored dolomite which extends to the bottom of the well and is at least 400 feet thick. The Permian Rico and the Pennsylvanian Hermosa formations could not be differentiated in the well, but would together make up the 1,500-foot interval above the anhydrite. This thickness contrasts strongly with the gross thickness of about 2,400 feet in the vicinity of the J. H. Shafer well No. 1 (Fig. 1, locality 14), and establishes a decrease in thickness of about 900 feet in 25 miles. The anhydrite-bearing beds are correlated with the Paradox formation and, like the overlying units, show a considerable thinning, even

[26] Sidney Paige, oral communication.

[27] David White, "Flora of the Hermit Shale, Grand Canyon, Arizona," *Carnegie Inst. Washington Pub. 405* (1929), p. 11.

if the normal thickness of 2,000 feet proposed on an earlier page be accepted, though the actual thickness is 4,100 feet. The cream-colored dolomite reported beneath the anhydrite is very different from the variegated shales underlying the Paradox formation in the J. H. Shafer well No. 1, farther east, and must be recorded as of unknown age. An assignment to the Mississippian seems most probable.

The oldest exposed rocks in the San Rafael Swell crop out in the Black Box Canyon of San Rafael River (Fig. 1, locality 1) and in Straight Wash (Fig. 1, locality 2), where interbedded buff to gray sandstone and limestone underlie a massive sandstone of Permian age. Although nearly 450 feet of this series is exposed in Straight Wash, its age has not been determined. Because of the differences in color and in general aspect from rocks known east of the Swell, and because of the known westward thinning of the Paleozoic formations above the Paradox, and apparently of the Paradox itself, it is at least possible that the Paradox, Hermosa, and Rico formations thin out entirely in the distance of 30 miles intervening between the outcrop of the sandstone-limestone series in Straight Wash and the Phillips Petroleum Company's well. The outcropping sandstone-limestone series in the lowest exposures in San Rafael Swell may be of Mississippian age and perhaps equivalent to the dolomite underlying the anhydrite in the Phillips Petroleum Company's well. If this suggested relation is the true one, the western limit of the Paradox formation falls definitely between the two points mentioned. If the sandstone-limestone series cropping out in the San Rafael Swell should eventually prove to be of either Rico or Hermosa age, there would remain no specific evidence of the location of the western limit of the saliferous beds. Because of the westward thinning of the saliferous beds from 4,100 feet at the J. H. Shafer well No. 1 to 700 feet at the Phillips Petroleum Company's well, both of which were drilled on similar folds, it seems unlikely that these beds continue many miles west of the location of the latter well.

Part of the outline of the basin in which the saliferous Paradox formation accumulated is thus known within narrow limits. As shown on the sketch map (Fig. 1), the basin lies mostly in Utah, and is elongate with a northwest trend, lying southwest of and parallel to the Uncompahgre uplift. The length of the short axis of the basin does not greatly exceed 80 miles. The length of the long axis can not be determined, but it probably exceeds 150 miles. The northwest end of the basin presumably lies a short distance northwest of Greenriver, Utah, but there is no evidence bearing on its exact position. No rocks that can be assigned to the Paradox formation have been reported from a well drilled by the Continental Oil Company, near Shiprock, New

Mexico (Fig. 1, locality 25), although it is believed by the writers that the well has been drilled into rocks of Mississippian age. The southeast end of the Paradox basin must therefore be in southwest Colorado or the extreme northwest corner of New Mexico.

According to the most commonly accepted theory of the accumulation of great thicknesses of saliferous beds,[28] the deposits result from the evaporation of sea water in a nearly landlocked arm of the sea. The basin must be sufficiently open to the sea to receive a constant ad-

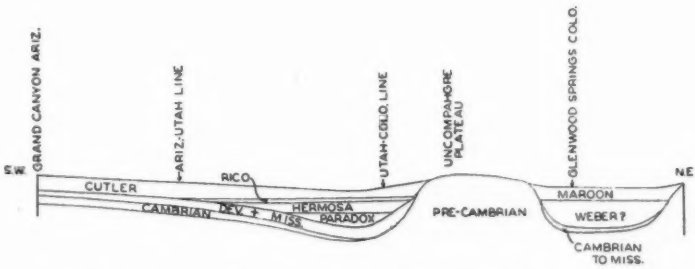

FIG. 2.—Stratigraphic relations of Paradox formation and relation of Paradox basin to basin in which Weber(?) formation accumulated. Horizontal distance, about 450 miles. Vertical exaggeration, about 25 times.

dition of sea water to replace the water lost by evaporation and to furnish a steady supply of salt, but the barrier to the open ocean must be of such a character as to prevent free circulation between the concentrated salt solution in the basin and the dilute sea water.

Fitting to this theory the known facts and the inferences concerning the Paradox basin, it appears that there was a definite barrier to the open sea on both the northeast and southwest sides, but that the basin was sufficiently open to the sea at one end to permit the repeated incursion of sea waters. Which end was relatively open to the sea can not be determined. Rocks of Pennsylvanian age are present in the Wasatch and Uinta mountains[29] northwest of the Paradox basin and are widely distributed as the Magdalena group in New Mexico[30] southeast of the Paradox basin. The Pennsylvanian rocks in the Wasatch and Uinta mountains, although they have not been studied in detail,

[28] Karl Ochsenius, *Die Bildung der Steinsalzlager und ihrer Mutterlaugensalze* (Halle, 1877).

[29] B. S. Butler, "The Ore Deposits of Utah," *U. S. Geol. Survey Prof. Paper 111* (1920), pp. 295 and 600.

[30] N. H. Darton, "Red Beds and Associated Formations in New Mexico," *U. S. Geol. Survey Bull. 794* (1928), pp. 18–19.

appear to be much thinner than they are in southeastern Utah and west of the Wasatch Mountains in the Oquirrh Range.[31] Rocks of Mississippian age are thin in the Wasatch Mountains as compared with the section in the near-by Oquirrh Range and at other outcrops west of the Wasatch Mountains.[32] These relations suggest that Mississippian rocks were exposed to erosion during at least part of Pennsylvanian time and this land mass perhaps served as a barrier to the open sea northwest of the Paradox basin during the accumulation of the Paradox formation, although later it was apparently covered by the Pennsylvanian sea. The suggestion therefore follows that the open end of the Paradox basin was towards the Magdalena sea in New Mexico.

The basin in which the Paradox formation was deposited appears to have been a structural basin (Fig. 2). A restoration of the conditions seems to indicate that the flat-lying limestone beds of Mississippian age were folded at the close of the Mississippian or early in the Pennsylvanian, forming structural basins which were filled by water of the Pennsylvanian sea. The Uncompahgre-San Luis highland, uplifted at this time, formed a ridge between two such structural basins. The Paradox formation accumulated in the basin southwest of this land area, and the "Weber shales" accumulated in the basin northeast of the land. Although believed to be contemporaneous, these basins do not appear to have been interconnected.

[31] James Gilluly, "Stockton and Fairfield Quadrangles, Utah," *U. S. Geol. Survey Prof. Paper 173* (1932), pp. 34–38.

[32] T. B. Nolan, oral communication.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 17, NO. 8 (AUGUST, 1933), PP. 981-1002, 34 FIGS.

SIMPLE PRINCIPLES OF EFFICIENT OIL-FIELD DEVELOPMENT[1]

H. D. WILDE, JR.[2] and F. H. LAHEE[3]
Houston and Dallas, Texas

ABSTRACT

The experiments described in this paper were performed to illustrate certain changes which are believed to affect the oil-water and gas-oil contacts in actual oil fields under certain conditions of oil production. They demonstrate the fact that slow, uniformly distributed extraction yields more oil, and yields this oil more efficiently, than rapid and irregularly distributed extraction. They show that where fine and coarse layers of sand alternate, there is a tendency for more rapid water encroachment in the coarser layers, with resulting by-passing and loss of oil in the finer layers. And they show further that conservation of the gas, and therefore of the gas energy, in a reservoir effects a larger ultimate recovery of the oil than if the gas is produced contemporaneously and without restriction. These experiments offer convincing proof of the advantages of proper utilization of the natural gas energy and the natural water drive within an oil reservoir.

INTRODUCTION

The experiments here described belong in two sets. One set was conducted by H. D. Wilde, E. P. Weatherly, and F. S. Westcot, at Houston, primarily for the use of the American Petroleum Institute, and the other set was conducted by F. H. Lahee and W. E. Winn at Dallas as one of the projects of the committee on applications of geology, of The American Association of Petroleum Geologists. Both sets of experiments were planned with the object of illustrating, under varying conditions of oil extraction, certain changes which are believed to affect the oil-water and gas-oil contacts in actual oil fields under similar methods of production. In both sets of experiments, although independently conceived and executed, the results were strikingly corroborative. They show in a simple manner some of the reasons for the oft-repeated counsel of petroleum geologists and engineers that an oil field should be systematically developed and operated with efficient utilization of reservoir energy.

Credit should be given here to R. Van A. Mills, who, more than 10 years ago, under the auspices of the United States Bureau of Mines,

[1] Read before the Association at the Houston meeting, March 24, 1933. Manuscript received, May 12, 1933.

[2] Humble Oil and Refining Company.

[3] Sun Oil Company.

built a tank with a glass front and studied the behavior of water, oil, and gas under varying conditions of extraction, more or less similar to the procedure followed by the present writers; but Mills' results[4] were perhaps a little premature, for the industry had not then been forced to realize their importance.

The series of experiments conducted at Dallas, being of a more elementary nature than those performed at Houston, is first described.

EXPERIMENTS BY LAHEE AND WINN

Apparatus and materials.—For the tests at Dallas, a tank made of sheet iron was used. The front face was of plate glass, $\frac{5}{8}$ inch thick, firmly bolted to the front edges of the tank and protected against leakage by rubber gaskets. Inside measurements of this tank were $7\frac{1}{2}$ inches front and back, 21.75 inches high, and 27.75 inches right and left (Fig. 1). The top was a piece of sheet iron which was bolted down by wing nuts after the tank had been loaded for experimentation. Openings, with valve connections, were provided, six on each side and three below (behind the wooden support).

For sand three grades were used, each separately. The coarsest was ordinary standard Ottawa cement-testing sand, consisting of well rounded quartz grains of approximately uniform size (20–30 mesh). This is here referred to as sand of grade A. It was used in experiments 1, 2, and 3, and as the matrix in experiments 4 and 5. A finer grade of sand, which is here called grade B, was used for the lenses in experiment 4. This consisted of rather poorly rounded quartz grains of sand which passed through a 30-mesh screen, but not a 40-mesh screen. The sand for the lenses in experiment 5 was still finer (grade C), of similar character to grade B sand, but composed of grains which passed through a 60-mesh screen, but not an 80-mesh screen.

The oil used in these experiments was kerosene stained brown by a little crude oil of 39° A.P.I. gravity. In this way this oil had a gravity of about 42° A.P.I. which probably compares favorably in fluidity or viscosity with crude oil of somewhat lower gravity when under the temperatures and pressures existing in reservoir sands at depths of 3,000 or 4,000 feet.

In order to subject the contents of the tank to somewhat more than atmospheric pressure, a 5-gallon bottle containing water was put on a shelf approximately $1\frac{1}{2}$ feet above the top of the tank, and was connected with the openings at the base of the tank in such a way that

[4] R. Van A. Mills, "Relations of Texture and Bedding to the Movements of Oil and Water through Sands," *Econ. Geol.*, Vol. 15 (1920), pp. 124–43; also, "Experimental Studies of Subsurface Relationships in Oil and Gas Fields," *ibid.*, Vol. 15 (1920), pp. 398–421.

the water could be siphoned out of the bottle and introduced through one or more of the valves in the base of the tank. To facilitate flushing of oil from the sand, caustic soda was dissolved in this water to make approximately a 4 per cent solution.

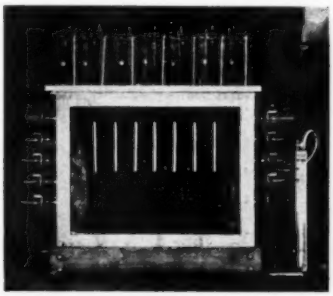

FIG. 1. Experiment 1.—Tank full of oil-saturated sand. All valves closed.[5]

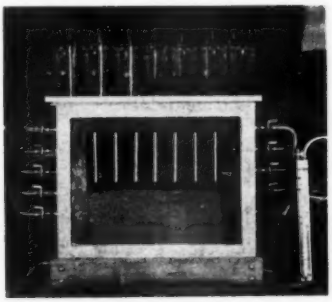

FIG. 3. Experiment 1.—Same as Figure 2, 13 minutes later.

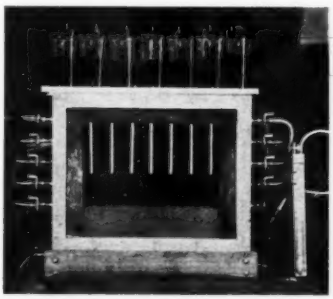

FIG. 2. Experiment 1.—Oil above (dark), water below (light). After oil had been withdrawn slowly and equally from the seven wells for 28 minutes.

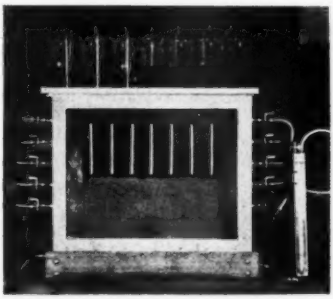

FIG. 4. Experiment 1.—Oil-water contact 45 minutes after extraction began.

Experiment 1.—The tank was partly filled with oil into which sand of grade A was evenly sifted until it reached a level about 2 inches below the top, with a layer of free oil 1 inch deep above it. The top of the tank was then placed on a rubber gasket and screwed tightly in place. A pressure of $1\frac{1}{4}$ pounds per square inch was applied inside the

[5] Figures 1–22 show experiments by Lahee and Winn. Figures 23–34 illustrate experiments by Wilde, Weatherly, and Westcot.

tank by opening the valve admitting water at the base. Figure 1 shows the tank in readiness for the experiment, filled and under pressure as described, and with all but the water valves closed. The seven strips of white paper are merely diagrammatic representations of seven wells. The actual openings of the tubes from which oil is to be withdrawn are $\frac{3}{16}$ inch behind the glass and about $\frac{1}{8}$ inch below the lower ends of the paper strips. From these points the tubes are bent to lead out at the sides of the tank, then round to the rear, and finally upward and forward to spill into the seven beakers seen in the figure. This

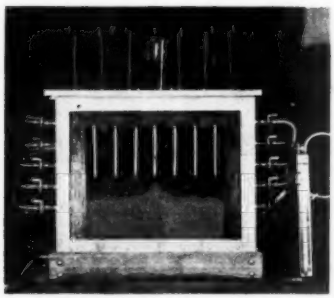

FIG. 5. Experiment. 2.—Oil withdrawn rapidly from one well resulting in coning of water.

arrangement permits handling of the top of the tank without in any way disturbing the tubes, the position of which can be accurately set while the tank is still empty. The fact that the tubes have a devious course does not in any way affect the relations of their lower openings within the oil-saturated sand. Each tube is provided with a needle valve in the rear as well as a stop-cock at the side of the tank. Having everything ready, all seven wells were allowed to flow at a slow rate made as nearly as possible the same for all. After 28 minutes the oil-water contact had risen to the level shown in Figure 2. Thirteen minutes later it had reached the level in Figure 3. Finally, 45 minutes after the start, the water had reached all seven wells, still with a nearly straight horizontal contact (Fig. 4). The total amount of oil withdrawn was 8,700 cubic centimeters, or an average of 27.6 cubic centimeters per well per minute.

This experiment demonstrates the effects of slow uniform extraction evenly distributed among wells which are evenly spaced.

Experiment 2.—This experiment was begun with the oil-water con-

tact horizontal and at a level about halfway from the bottom of the tank to the lower ends of the wells. This was merely to save time in extraction. Pressure was applied as before, and oil was then withdrawn through one well only, wide open. After 12 minutes a cone of water had developed as shown in Figure 5. As soon as this cone reached the well opening, water began to be produced with the oil, and very soon a large percentage of the production had become water. This experiment illustrates the well-known coning effect of bottom water where extraction is too rapid.

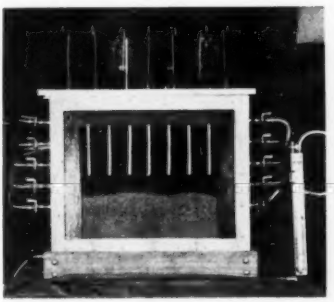

FIG. 6. Experiment 3.—Oil withdrawn rapidly through two wells. Water cones beginning to form.

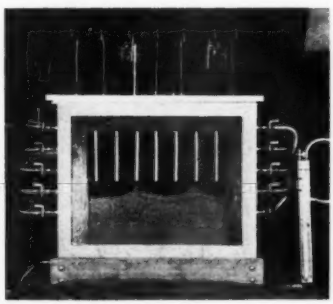

FIG. 7. Experiment 3.—Same as in Figure 6, after water cones have risen to openings of wells, and water has begun to come out with oil.

Experiment 3.—In order to illustrate the effects of too rapid extraction from adjacent wells, the oil-water contact was again brought to a level 6 inches below the well openings inside the tank. Pressure was applied and two wells were opened wide. Figure 6 shows the shape of the contact after 8 minutes. Cones are beginning to form. In Figure 7, these cones have risen so high that water is being produced in each well. Between the cones is a body of oil which represents what may be lost or "wasted" in actual oil pools where extraction is so rapid that the water can not follow up after the oil in a gradual and orderly manner as in experiment 1. In this experiment 3,300 cubic centimeters of oil were taken out by the two wells in 15 minutes, or at an average rate of 110 cubic centimeters per well per minute, four times as fast as in experiment 1. It is obvious that any method of production which is designed to yield oil economically, with least waste of the oil and with extraction of the least amount of water along with the oil, must include the factors of even spacing of the wells, and pinching down

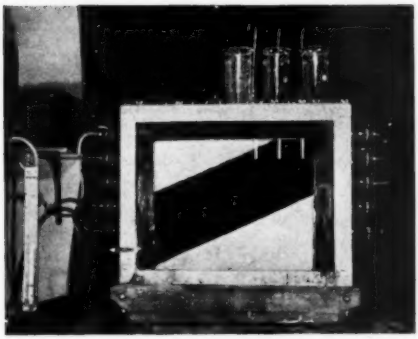

FIG. 8. Experiment 4.—Tank containing inclined layer of oil-saturated sand (dark) between two layers of impervious clay (white). In the sand layer are two lenses of fine sand (30–40 mesh). All valves closed.

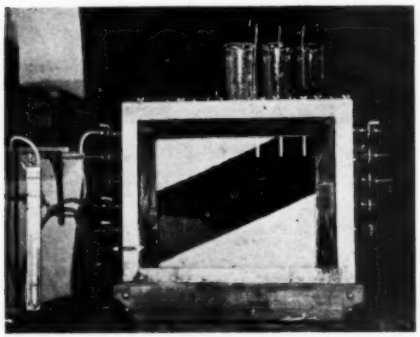

FIG. 9. Experiment 4.—Oil being produced by one well. Water has risen from lower part of inclined sand layer (cf. Fig. 8). 4 minutes after commencement.

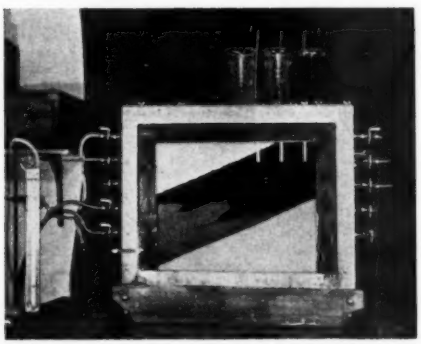

FIG. 10. Experiment 4.—Water by-passing lenses, 9 minutes after commencement of experiment.

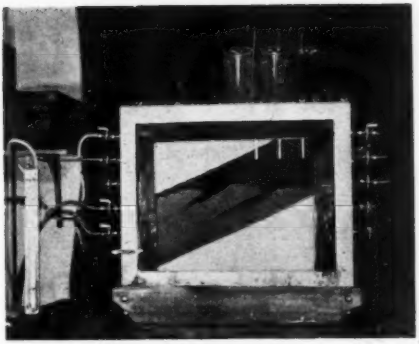

FIG. 11. Experiment 4.—Oil in lower lens nearly isolated, 15 minutes after commencement.

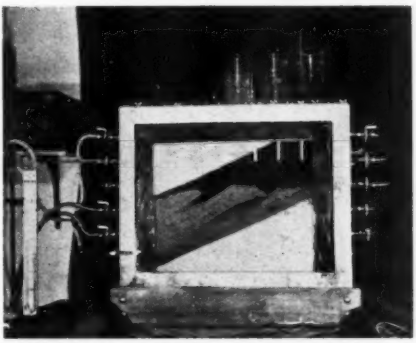

FIG. 12. Experiment 4.—Oil in lower lens isolated and permanently lost.

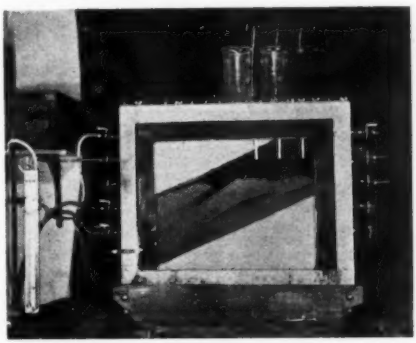

FIG. 13. Experiment 4.—Similar to Figure 12, 2 minutes later.

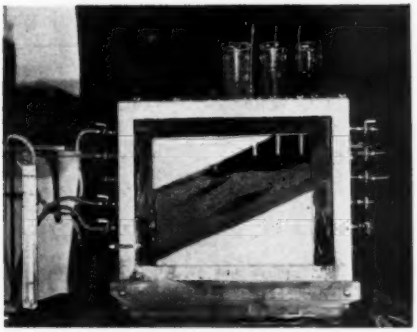

FIG. 14. Experiment 4.—Oil in both lenses trapped by water which has completely by-passed lenses, 18 minutes after commencement. Cone developing under well from which oil has been withdrawn.

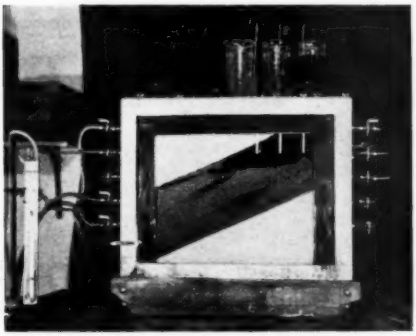

FIG. 15. Experiment 4.—Water cone fully developed under producing well.

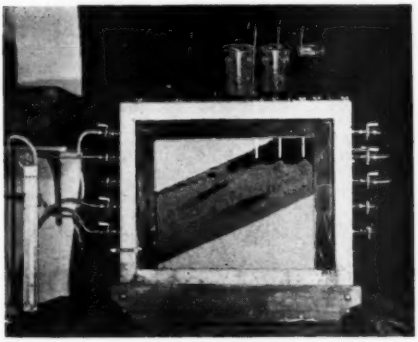

FIG. 16. Experiment 4.—Right well closed, and other two wells opened, with result that water cones are formed under each. Note that amount of oil trapped in lenses remains the same as at time of complete by-passing (Fig. 14).

the yield of all the wells to a relatively small and uniform quantity per day.

Experiments 4 and 5.—Figures 8 to 16 illustrate different stages in experiment 4, and Figures 17 to 22, different stages in experiment 5, both experiments being arranged to show the results of oil extraction and consequent water invasion where a sand is not of uniform grain. In experiment 4, lenses of 30–40 mesh sand were built into the main mass of Ottawa (20–30 mesh) sand. In experiment 5 the sand lenses are of 60–80 mesh sand, therefore considerably finer than in experiment 4. As nearly as possible these lenses were made of uniform cross

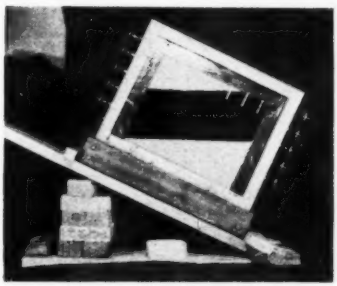

FIG. 17.—Showing method of loading tank for experiments 4 and 5.

section from front to back, that is, from the glass to the rear wall of the tank. In loading for both experiments, the tank was set at an angle, as in Figure 17. The lower right corner was filled with a plastic clay, composed largely of bentonite, carefully moulded and pressed to fill all spaces, and then leveled off to form a floor for the sand. Oil was then poured in, and sand was sifted into this until the body of oil-saturated sand, including the two finer lenses, was 8 inches deep. Then clay was moulded into the remaining part of the tank, which was then lowered back into normal position, resting on its base (Fig. 8). After screwing the top in place, pressure was applied as before.

In experiment 4, oil was withdrawn from one well (Figs. 9–15). As the water followed the oil, it soon revealed a decided tendency to by-pass the fine-grained lenses (Figs. 10, 11). The same effects were observed in experiment 5 (Figs. 18–20); but in this case a much larger proportion of the oil was left in the lenses which were of finer grain than those in experiment 4. The figures illustrate the successive stages in the by-passing of these lenses.

In comparing the results in these two experiments, it will be observed that after the main oil-water contact breaks away (separates) from the lens (Figs. 12, 14, 21), no more oil passes out of the lens (cf. oil in lower lens in Figs. 12–16). The oil left there is permanently lost.

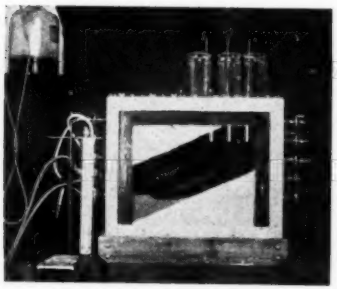

FIG. 18. Experiment 5.—Inclined layer of sand (20–30 mesh) with two lenses of fine sand (60–80 mesh), all saturated with oil. Here oil is being withdrawn from well on right. Water, in rising, is just beginning to pass between lenses.

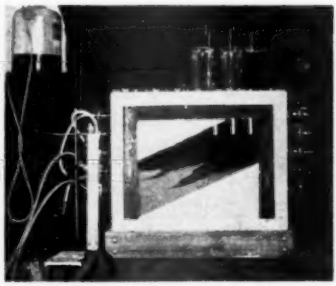

FIG. 20. Experiment 5.—Same as Figures 18 and 19. Water has passed far up between lenses and on each side of them, leaving them still nearly full of oil.

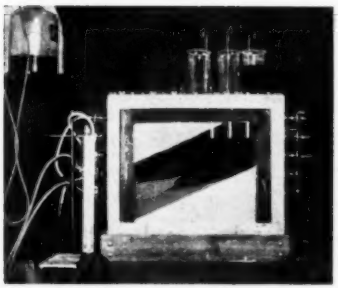

FIG. 19. Experiment 5.—Same as Figure 18, a few minutes later.

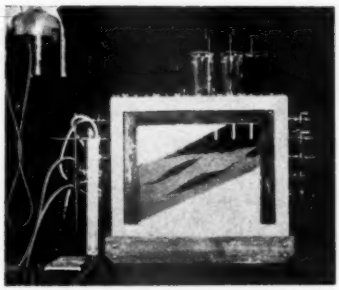

FIG. 21. Experiment 5.—Oil in both lenses completely trapped by water which has passed on beyond them.

Also note that a much larger proportion of oil is left in the finer sand lenses (cf. Figs. 15 and 21).

In experiment 4 the rate of extraction from the one well was 385 cubic centimeters per minute, and in experiment 5, 225 cubic centimeters per minute. A total of 7,700 cubic centimeters was withdrawn

in experiment 4, and a total of 7,900 cubic centimeters in experiment 5 before the well commenced to produce water.

Experiments 4 and 5 demonstrate the fact that relatively rapid production of oil develops a tendency to by-passing and loss of oil in the more finely grained sand layers due to the greater rate of withdrawal of the oil and advance of the bottom water in the coarser layers. This tendency increases with increase in the difference of texture (and permeability) of the separate sand layers. That some oil does come out of the finer layers is evident in Figures 11 to 16, and 22. With

FIG. 22. Experiment 5.—Close-up view of lenses of fine sand in experiment 5, after some oil had been returned into coarser sand. This shows that lenses yielded only very small amount of oil (white border) before they were isolated (as shown in Figure 21).

slower rate of extraction there would be more time for the fine layers to yield their oil content. However, quite likely in an actual oil pool, the very fine layers would never yield all their oil within the limits of time permissible for most economical operation. Nevertheless, the nearest approach to complete extraction in any pool would clearly be through slow and even production of the oil, thus as far as possible facilitating the flushing of the finer sand layers and diminishing the ultimate loss.

EXPERIMENTS BY WILDE, WEATHERLY, AND WESTCOT

Apparatus and materials.—The tank used in the experiments performed at Houston is shown in Figure 23. It is a box made of aluminum, 45 inches long, 20 inches high, and 6 inches from front to back.

The front has a window 40 inches long and 14 inches high into which a sheet of plate glass $\frac{1}{2}$ inch thick is fitted. The cover is removable to permit filling the box, and can be securely fastened in place by means of stud bolts around the top. Five stuffing boxes are provided in the cover through which "wells" can be inserted to any desired depth. The "wells" are lengths of $\frac{1}{8}$-inch pipe each, with a conically pointed plug in the lower end and the lower $\frac{3}{4}$-inch perforated with $\frac{1}{64}$-inch holes. Fluids may be introduced or withdrawn through any of a number of connections inserted through the ends and bottom. Ordinarily these are closed by stopcocks.

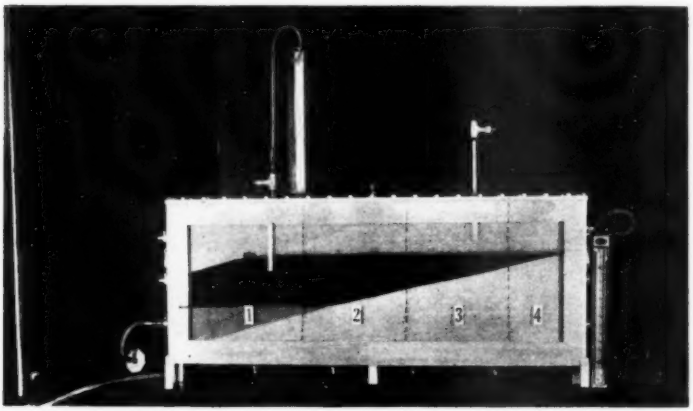

FIG. 23.—Laboratory model showing fluid levels at beginning of experiments made by Wilde, Weatherly, and Westcot.[6] Total oil, 5,500 cubic centimeters.

By filling the space between the front and the back of the box with layers of sand saturated with water, oil, or gas or with plastic clay, any desired combination of conditions can be reproduced. The plastic clay is a stiff mixture of clay and water of about the same consistency as putty.

In each experiment of this series, the tank was filled as shown in Figure 23. The sand layer slopes down from right to left to represent a section of an oil-field reservoir on the side of a dome or anticline or a portion of a monocline. The lower portion of the box is filled with plastic clay with its upper surface sloping down and to the left. Above this clay, there is a layer of sand about 8 inches high and on top of

[6] Figures 23–34 show experiments by Wilde and collaborators. Figures 1–22 show experiments by Lahee and Winn.

this there is more plastic clay. The lower portion of the sand layer is saturated with water and appears dark gray in the picture; the middle portion is saturated with oil and appears black; the upper portion is saturated with gas and appears light gray. Two wells are inserted through the upper clay with the perforations in the sand layer. The wells are placed midway between the front and back and can not be seen through the glass window, but their position is indicated by a strip of paper pasted on the glass. As only the lower $\frac{3}{4}$-inch of the pipe is perforated, the well may be considered to be located at the lower extremity of the paper strip; and it will be observed that the well in section 1[7] is located in sand saturated with oil and that the one in section 3 is located in oil-free gas sand. The black paper strips pasted on the front are to show the position of the original boundaries of the oil as the experiment progresses.

A total of 5,500 cubic centimeters of crude were used in saturating the oil sand. This crude had been blended with a small amount of kerosene in order to reduce the viscosity of the oil and make it similar to the viscosity actually existing in a sand reservoir. The sand was a screened Ottawa sand of uniform texture, the same as that used by Lahee and Winn. This sand is coarser than the sand in most oil fields, but was used so that the experiments could be completed in a reasonable length of time. The oil used differed from that in an actual reservoir in that it was not saturated with gas, but inasmuch as the glass window in the model would not stand a pressure exceeding 2 or 3 pounds per square inch, practically no gas could be held in solution in the oil. In an actual reservoir, the free gas lying above the oil is originally under pressure and as the pressure on the gas is reduced, the space occupied by the gas increases, either by being withdrawn from the reservoir or expanding within the reservoir and pushing the oil away from the free gas area. The inability to use pressure in this model made it impossible to reproduce the expansion of the gas by the reduction of pressure and to make up for this deficiency, gas from an outside source was introduced into the free gas space during the course of the experiment. In spite of these limitations, it is believed that the model illustrates the behavior of actual reservoirs. Water can be introduced into the model from a container standing about 3 feet above the model through the connection on the lower left-hand end of the box. This water flows into the water-saturated sand and represents a water drive in an actual field. The manometer at the right-hand end of the box is merely for the purpose of indicating the

[7] For purposes of description, the tank is shown divided into four vertical sections, numbered from left to right.

pressure within the model and is used as a safety measure. The pressures indicated by the manometer have little significance with respect to the experiments themselves.

Experiment 1.—The first of the three experiments is designed to show the beneficial results of conserving the gas energy by keeping the free gas wells and the high gas-oil ratio wells shut in, and the efficient use of the water drive by producing the oil wells at a slow rate. The well in section 3 (Fig. 23) represents wells located in the free gas area and wells that can produce only with a high gas-oil ratio. Although it is true that in the model this well could be inserted deeper and thus penetrate the oil-saturated sand, it represents actual wells in which oil sand does not lie beneath the wells and hence cases where deeper drilling will not penetrate the oil sand. In this experiment, this gas well was kept shut in, in order to conserve the gas in the free gas area. The well in section 1 represents low gas-oil ratio oil wells. It was produced at a low rate (approximately 25 cubic centimeters per minute) by adjusting the needle valve above the well. A constant hydrostatic head was maintained on the water sand through the connection at the lower left side. A small amount of gas was introduced into the free gas area to imitate the increase in volume of the gas in the free gas area.

After the oil well had been producing for approximately 30 minutes, the changes shown in Figure 24 had taken place. The well had produced 760 cubic centimeters of oil or 14 per cent of that used in saturating the sand. It may be observed that the water had advanced into the sand originally saturated with oil, the portion of the oil sand flooded with water being noticeable because of its being darker than the original water-soaked sand. The new boundary between the oil and water was level and relatively smooth. The expansion of the free gas had pushed the oil-gas boundary down a short distance and here again the new boundary was level and comparatively smooth.

Figure 25 shows what had taken place by the time the oil well had been producing for an hour and 20 minutes. The well had produced 2,000 cubic centimeters of oil, which is equivalent to 36 per cent of the oil originally in the sand. The water had advanced far into the oil sand, but the boundary between the water and the oil is still comparatively smooth and almost level, although there is a tendency for the boundary to slope slightly down and toward the right. The expansion of the free gas had pushed the oil-gas boundary down farther, but the boundary remained smooth and practically level.

Figure 26 shows the model at the end of 2 hours. Water had advanced to the point where it had completely flooded out the oil well

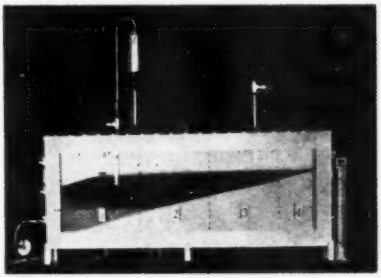

FIG. 24. Experiment 1.—Fluid levels after 30-minute production: 760 cubic centimeters, or 14 per cent of original oil.

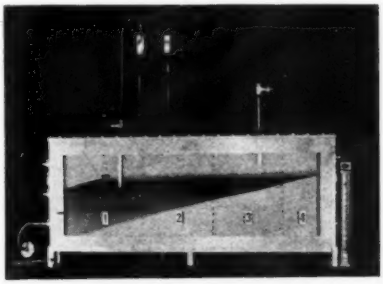

FIG. 25. Experiment 1.—Fluid levels after 1 hour and 20 minutes production: 2,000 cubic centimeters, or 36 per cent of original oil.

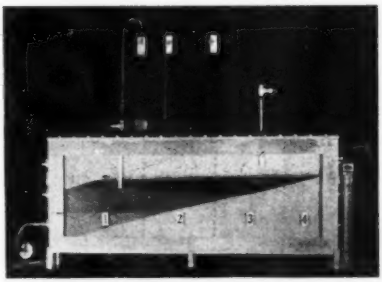

FIG. 26. Experiment 1.—Fluid levels after 2-hour production: 2,800 cubic centimeters, or 51 per cent of the original oil and 200 cubic centimeters of water.

and at this time, the left-hand well was producing nothing but water. The well had produced 2,800 cubic centimeters of oil and 200 cubic centimeters of water. This represents a production of 51 per cent of the oil put into the reservoir, which, of course, is a high recovery. The oil-water boundary is not exactly level, but the slope is not steep and the boundary is relatively smooth. The oil-gas boundary has been depressed, but it is smooth and practically level. It is obvious that the conservation of the gas and the slow rate of oil withdrawal had brought about highly desirable conditions in the reservoir sand.

Experiment 2.—The second experiment in this series was designed to show the inefficient use of the water drive by producing the oil well at too rapid a rate. The box was recharged with fresh sand, water, oil, and gas to reproduce exactly the original conditions of the first experiment. As in the first experiment, the well on the right, representing wells that would produce free gas and oil with high gas-oil ratios, was kept shut in. The oil-producing well on the left was allowed to produce at a rate of approximately 75 cubic centimeters per minute, or three times as fast as in the first experiment. Thus, the only difference between the first and second experiments was the rate at which the oil well produced.

After the well had been producing for 3 minutes, it had produced approximately 220 cubic centimeters of oil, which is equivalent to 4 per cent of the 5,500 cubic centimeters of oil used to saturate the sand. The appearance of the model at this stage is shown in Figure 27. The water had advanced irregularly into the oil sand with a tendency towards fingering and the boundary was considerably higher at the left-hand end, sloping downward toward the right. The oil-gas boundary had been depressed slightly and was relatively smooth and level.

Figure 28 shows the progress that had been made after about $6\frac{1}{2}$ minutes with a production of 480 cubic centimeters, or nearly 9 per cent of the oil originally present in the sand. The water was still advancing irregularly and the boundary sloped down and toward the right. The oil-gas boundary was smooth but was depressed more at the left end than at the right.

Figure 29 shows conditions at the time when the well was completely flooded with water and thus at the same stage as when the last picture of the first experiment was taken. The well had been producing for 16 minutes and had produced 1,200 cubic centimeters of oil, or 22 per cent of the oil originally present in the sand. The well had also produced approximately 100 cubic centimeters of water. The water-oil boundary is very irregular and slopes steeply from the well toward the right. The boundary also slopes down and to the left away

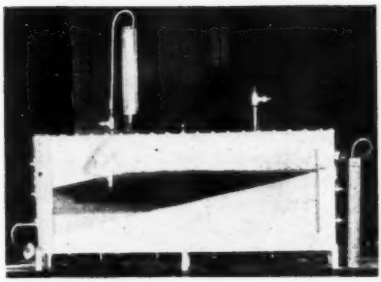

FIG. 27. Experiment 2.—Production rate 75 cubic centimeters per minute, oil well flowing, gas well shut in. Fluid levels after 3-minute production: 220 cubic centimeters, or 4 per cent of original oil.

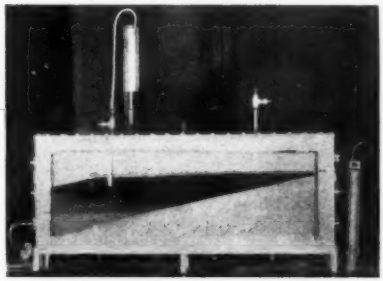

FIG. 28. Experiment 2.—Fluid levels after 6½ minute production: 480 cubic centimeters or 9 per cent of original oil.

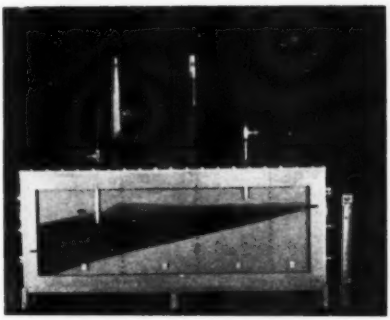

FIG. 29. Experiment 2.—Fluid levels after 16-minute production: 1,200 cubic centimeters, or 22 per cent of original oil and 100 cubic centimeters of water.

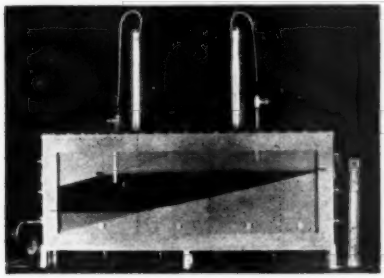

FIG. 30. Experiment 3.—Production rate 25 cubic centimeters per minute, both wells flowing. Fluid levels at commencement.

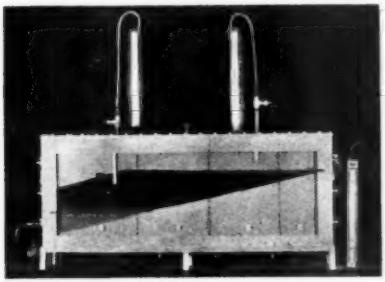

FIG. 31. Experiment 3.—Fluid levels after 3-minute production: 70 cubic centimeters, or 1.3 per cent of original oil.

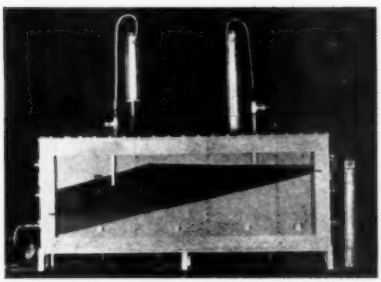

FIG. 32. Experiment 3.—Fluid levels after 16-minute production: 400 cubic centimeters or 7.3 per cent; second well has produced only gas.

from the well, but the slope here is not as steep. The oil-gas boundary has been depressed more at the left end than at the right, but it is quite smooth.

In this experiment, differing from the first only in the rate at which the oil well was produced, less than one-half as much oil was produced when the water and gas advance had reached the same stage and the coning of the water was much more serious. The conclusion is obvious.

Experiment 3.—The third experiment of the series was designed to show the harmful effects of wasting the energy in the free gas area together with the rapid advance of water caused by the rapid withdrawal of the free gas. The box was charged with sand, water, oil, and gas in exactly the same manner as for the first and second experiments. The oil well on the left was allowed to produce at the same rate as in experiment 1, that is, at a rate of approximately 25 cubic centimeters per minute. The well on the right was allowed to produce throughout the experiment, producing gas during the first part and oil at a high gas-oil ratio during the last part. The appearance of the model just before production was started is shown in Figure 30.

After the production had proceeded for about 3 minutes, the picture shown in Figure 31 was taken. The oil well had produced about 70 cubic centimeters of oil, or 1.3 per cent of the oil originally in the sand. Although only a small amount of oil had been produced, the production of the gas had permitted the water drive to force oil from the sand which was originally filled with free gas. The strip of black paper pasted on the glass at the left of the oil well shows the original position of the oil-gas boundary. This boundary has been elevated more at the left end than at the right. That portion of the gas sand that has been invaded with oil can be identified in the picture because it is a little lighter in color than the sand originally saturated with oil. In pushing the oil into the gas sand, the water has advanced into the oil sand at a rapid rate and the boundary between the water and oil is irregular and slopes down and toward the right.

Figure 32 was taken about 16 minutes after production had been commenced. By this time, the oil well had produced 400 cubic centimeters, or 7.3 per cent of the oil originally in the sand. The water drive had pushed the oil up into the gas sand to the point where it had just reached the well on the right, but this well was still producing nothing but gas. A large portion of the oil that had been in the oil sand was now in the gas sand. The water had advanced rapidly and the boundary between the oil and the water was very irregular.

Figure 33 was taken 22 minutes after production had commenced. The oil well on the left had produced 550 cubic centimeters of oil

and 25 cubic centimeters of water and thus 10 per cent of the oil in the sand had been produced from this well. The well on the right had produced 50 cubic centimeters of oil, or approximately 1 per cent of the oil originally in the sand, but all of this oil was produced at a

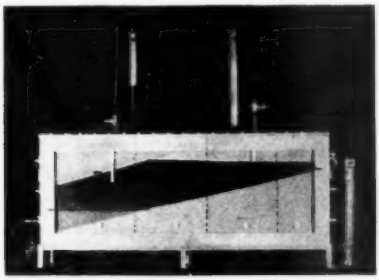

FIG. 33. Experiment 3.—Fluid levels after 22-minute production: 550 cubic centimeters or 10 per cent of original oil and 25 cubic centimeters water from well No. 1; 50 cubic centimeters, or 1 per cent oil, from well No. 2.

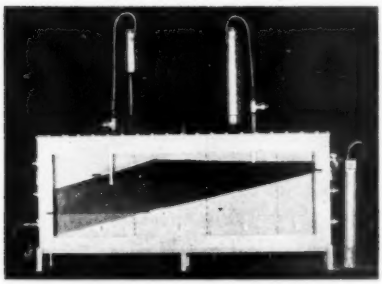

FIG. 34. Experiment 3.—Fluid levels after 30-minute production: 650 cubic centimeters, or 12 per cent of original oil and 100 cubic centimeters of water from well No. 1 and 80 cubic centimeters, or 1.6 per cent oil from well No. 2.

very high gas-oil ratio. The water drive had continued to push the oil into the dry gas sand, elevating the boundary a little more on the left than on the right end. The water-oil boundary was irregular and had reached the left-hand well.

Figure 34 was taken at the end of 30 minutes, when the production

had reached the same stage at which the other two experiments had been stopped. The left-hand well had produced 650 cubic centimeters of oil, representing a production of 12 per cent, and during the last few minutes of production, had produced 100 cubic centimeters of water. The right-hand well had produced 80 cubic centimeters of oil, or 1.6 per cent. All of the oil of the right-hand well had been produced with a high gas-oil ratio. The water drive had pushed a large portion of the oil out of the oil sand into the gas sand. The boundary between the oil and the water was irregular and far from level.

The movement of the oil into the dry gas sand is objectionable because the sand grains become coated with a film of oil which is not removed in the course of production, and, consequently, this oil is lost. Furthermore, the wells from which this oil can be produced will yield oil with a high gas-oil ratio, and the energy of the gas will have been dissipated long before a substantial quantity of the oil moved into the gas sand has been produced. Thus, there is a decided loss in permitting the oil to move into the gas sand.

After this phase of the experiment had been concluded, the right-hand well was allowed to produce until it was flooded out with water. The total amount of oil produced in both wells was 1,800 cubic centimeters, which represents only 33 per cent of the oil that was put into the sand. This is in contrast with the 51 per cent that was produced in the first experiment described above. In experiment 1, after the first phase had been finished, production from the well was continued until all of the oil possible was produced. The total amount recovered was 3,800 cubic centimeters, or 69 per cent. Thus, when both experiments were carried to the absolute limit, the first experiment had produced 69 per cent, whereas the third experiment had produced only 33 per cent.

CONCLUSIONS

In summarizing the three experiments, it is observed that where the gas well was shut in and the oil well allowed to produce at a slow rate, the recovery was 51 per cent of the oil in the reservoir, the water advanced evenly without the tendency to cone toward the producing well, and the expansion of the free gas forced oil towards the oil well. In the second experiment, where the gas was conserved but the production from the oil well was taken at a rapid rate, the recovery was only 22 per cent and the water showed a decided tendency in coning toward the producing well. In experiment 3, where gas from the free gas area was produced and wasted, the recovery was only 11.3 per cent. The oil well was produced at a slow rate, but the production of

the gas permitted the water to advance at a rapid rate and all of the objectionable features of rapid production from the oil well resulted. Because the water drive was able to force oil into the dry gas area, the ultimate recovery from the reservoir was materially reduced. In the third experiment, the owner of the right-hand well was able to convert his gas well into an oil well and recover some oil but only at a tremendous sacrifice on the part of the reservoir as a whole. This series of experiments shows very clearly the advantages of conserving the energy in the free gas area and making efficient use of the water drive by producing the oil wells at a slow rate.

These experiments, both those conducted by Wilde, Weatherly, and Westcot for the Institute and those conducted by Lahee and Winn, should convince the layman that statements made by petroleum engineers as to the merits of conserving the energy in the free gas area of an oil field and of producing the oil wells at low rates in order to use the water drive efficiently are based on a substantial foundation and are not the results of pure theory and speculation.

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VOL. 17, NO. 8 (AUGUST, 1933), PP. 1003-1015

GEOLOGICAL NOTES

CRETACEOUS SEDIMENTS IN CROWLEYS RIDGE, SOUTHEASTERN MISSOURI[1]

In June, 1932, while engaged in geomorphologic studies at the head of the lower Mississippi Valley, the writer happened to find high on the southeast facing bluff of Crowleys Ridge, near Ardeola, Stoddard County, Missouri, a bed of greenish glauconitic clay 4–5 feet thick, containing molds of marine shells, including several belonging to species of Ripley (Upper Cretaceous) age, as determined by L. W. Stephenson. The bed is exposed at an altitude of 430 feet above sea-level, that is, at a height of 110 feet above the floor of the Mississippi Valley. Inasmuch as Crowleys Ridge is generally supposed to consist throughout of Eocene sediments, and as the Cretaceous in southeastern Missouri has hitherto been found only in well borings, at depths of several hundred feet beneath the floor of the Mississippi Valley, this discovery was somewhat unexpected. From no part of Missouri, for that matter, have any outcrops of Cretaceous beds been reported heretofore, nor have any Cretaceous fossils been found, even in the deep wells referred to.

H. A. Buehler, state geologist of Missouri, after learning of the discovery, in January, 1933, detailed W. Farrar, of his staff, to collect more of the fossiliferous glauconite from the Ardeola locality. This Farrar did, but the material sent in by him proved to contain Eocene as well as Cretaceous forms (for lists of species, see last part of article). Further investigation being deemed desirable, Stephenson, on March 29, 1933, visited the locality in company with Farrar and H. S. McQueen of the Missouri Bureau of Geology and Mines. Immediately beneath the glauconite they found a 4-foot bed of ferruginous clayey sand containing many imprints of Ripley mollusks. This bed they determined to be at the top of the Ripley formation (representing the Owl Creek tongue), while the glauconitic bed represents a part of the Clayton formation (Eocene, lower part of Midway group). The Cretaceous forms included in the lower part of the glauconitic bed are merely an admixture that must have been derived from the Ripley sand below by mechanical processes, before the calcium carbonate had been leached from the fossils.

[1] Published by permission of the director of the United States Geological Survey.

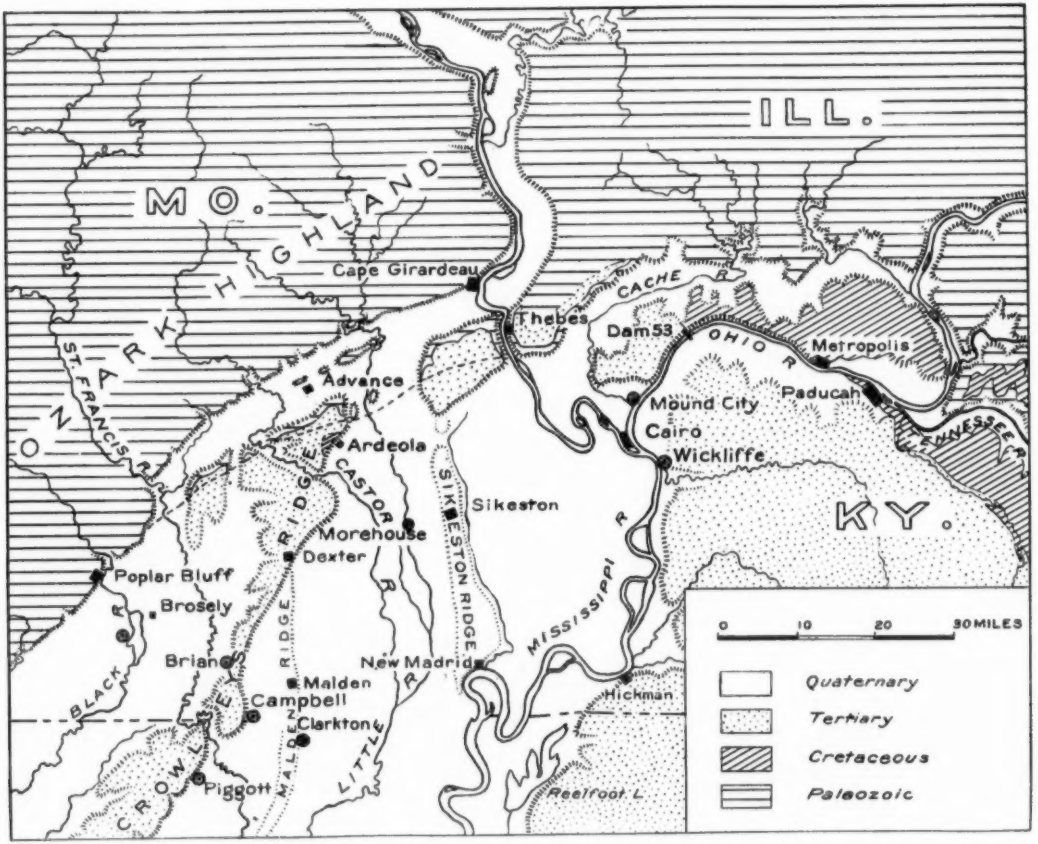

FIG. 1.—Geologic map of head of Mississippi embayment, showing location of Cretaceous beds in Crowleys Ridge near Ardeola, Missouri. Deep wells indicated by circles. Broken line extending from Mississippi gorge near Thebes, Illinois, south,

The contact between the Cretaceous sand and the overlying Eocene clay was found to be very distinct. "Although the contact . . . is somewhat obscured by weathering," Stephenson states, "its position can readily be determined within a vertical distance of one inch."

No fossils were found at lower levels in the bluff, although beneath the fossiliferous sand there are exposed to view fully 75 feet of Cretaceous strata consisting of irregularly bedded sand and interstratified laminae of sand and sandy clay. Near the base, it may be added, is a bed of lignite 15 inches thick that has heretofore been regarded as belonging to the Wilcox (Eocene) formation. Stephenson believes that these beds represent the McNairy sand member of the Ripley formation.

Above the glauconitic bed there is 35–40 feet of gray clay, presumably the Missouri representative of the Porters Creek clay (upper part of Midway group). Above this are, in turn, 6 feet of Pliocene gravel and 5 feet of Pleistocene loess.

On the top of Crowleys Ridge, about 0.65 mile northwest of the exposure in the bluff, another outcrop of the fossiliferous Ripley sand and the overlying glauconitic Eocene clay was found by the party, and here another collection of fossils was made. The Ripley sand here has an altitude of 480 feet above sea-level, or 50 feet above its position in the bluff. It therefore appears to have a southeasterly dip averaging 75–80 feet to the mile, and the Cretaceous-Eocene contact dips with it.

Crowleys Ridge, it is evident from the foregoing, contains near Ardeola a considerable body of Upper Cretaceous that reaches almost to its summit. The lateral extent of that body remains to be determined, but the fact of its presence meanwhile is sufficiently well established to justify a revision of prevailing ideas regarding the structure of Crowleys Ridge and, to some extent, of the geosyncline of Cretaceous and Tertiary strata that fills the upper part of the Mississippi embayment.

Crowleys Ridge is a strip of hilly upland of varying width that extends, interrupted by gaps, 200 miles longitudinally through the lower Mississippi Valley—from its head in southeastern Missouri as far south as Helena, Arkansas. Aside from the detached remnants of Pliocene gravel that cap its highest hills, and the thick mantle of loess that envelopes almost its entire body, aside also from the masses of Paleozoic limestone that are incorporated in its northernmost parts, the ridge is composed wholly, according to prevailing ideas, of sediments belonging to the Wilcox, Claiborne, and Jackson formations of the Eocene, the beds dipping gently toward the southeast and over-

FIG. 1.—Geologic map of head of Mississippi embayment, showing location of Cretaceous beds in Crowleys Ridge near Ardeola, Missouri. Deep wells indicated by circles. Broken lines show limits of Quaternal gravel terrace. Thebes, Illinois, south.

lapping one another in orderly succession. That part of the ridge in Missouri in which the Ripley and Clayton beds occur has heretofore been regarded as composed of Wilcox beds.

This simple conception of the structure of Crowleys Ridge is of course in harmony with the general conception of the arrangement of the Cretaceous and Tertiary strata in the Mississippi embayment in the form of a spoon-shaped geosyncline, the beds all dipping gently from the periphery inward, disturbed only by minor flexures. The eastern half of the geosyncline very probably has a simple spoon-shaped structure, to judge from the concentric arrangement of the outcrops, more especially of the Upper Cretaceous formations, which form the outer border. These formations crop out in an almost continuous belt extending northward through Mississippi and Tennessee, and curving northwestward through Kentucky, and westward and southwestward through southern Illinois. The western half of the geosyncline, however, is decidedly more irregular. This fact was already somewhat evident from the varying depths at which the Cretaceous has been reported in deep wells, but it is now suddenly made conspicuous by the discovery of Ripley and overlying Clayton beds in Crowleys Ridge at a height of 160 feet above the plain of the Mississippi.

A short distance southwest of Dam 53, on Ohio River, about 15 miles northeast of Cairo, Illinois, the Ripley beds dip below the surface, and thence westward and southwestward they slope down to increasingly great depths. If the interpretations that have been placed on the available well logs are at all reliable, the Ripley formation at Mound City, Illinois, would be at a depth of 280 feet beneath the Mississippi Valley; at Cairo, Illinois, at a depth of 500 feet; at Wickliffe, Kentucky, at a depth of 615 feet. Or, to state its positions with respect to sea-level: at Dam 53, its elevation is +370 feet; at Mound City, +38 feet; at Cairo, −186 feet; at Wickliffe, −295 feet. In southeastern Missouri the Ripley has been reported at the following levels: at Morehouse, −165 feet; at Brian, −280 feet; southwest of Brosely, −654 feet; at Campbell, −630 feet; at Clarkton, −931 feet. At Piggott, Arkansas, the Ripley appears to have been struck at −324 feet.

With these low levels the altitude (+480 feet) which the Ripley attains on Crowleys Ridge stands in striking contrast. It is to be noted, however, that none of the wells enumerated is in the close vicinity of Ardeola. The nearest well—that at Morehouse—is 15 miles distant in a southeasterly direction. All are farther south from the head of the Mississippi embayment than the Ardeola locality,

and consequently lower levels for the Cretaceous would be expected in all of them. It is therefore impossible to base on the disparities in level indicated any safe conclusions as regards the nature of the body of Cretaceous sediments in Crowleys Ridge.

That this body is not simply a hill or ridge on the upper surface of the Cretaceous due to erosion prior to the deposition of the Eocene, however, is in any event certain, for it carries on its summit a remnant of the Clayton formation, which is known to be at the base of the Eocene column. It is significant, further, that at Bell City, only 2 miles northeast of Ardeola, the bluff of Crowleys Ridge is composed in large part of quartzite (locally indurated sand) that is usually considered to be a characteristic feature of the Wilcox formation; while 3 miles farther south, near Zeta, the bluff consists chiefly of Porters Creek clay. There thus appears to be indicated a deformation of some magnitude; but what manner of deformation, whether by folding or by faulting, or by both, it is as yet impossible to say. It is greatly to be hoped that an attempt will soon be made to clear up this question by tracing the Cretaceous beds in the bluff of Crowleys Ridge from Ardeola, northeastward to Bell City and southward to Zeta, and determining their relations to the formations that are there exposed.

A more complete description of the locality near Ardeola at which the glauconitic bed was first found follows: at sharp bend in road leading northwestward from Ardeola, Stoddard County, Missouri, about half way up on southeast-facing bluff of Crowleys Ridge (portion locally known as Bloomfield Ridge); 0.35 mile in airline northwest of Ardeola railroad station, about 430 feet above sea-level or 110 feet above base of ridge; exposures in small cuts on both sides of road.

The bed of greenish glauconitic clay is 4–5 feet thick, containing irregular iron concretions and numerous prints and internal molds of marine shells. Most of the glauconite grains have a concentric structure, each having a core enveloped by an outer layer of glauconite with radial structure.

The material collected by F. E. Matthes and James K. Rogers, June 13, 1932, (U.S.G.S. Coll. 16,221) contained the following forms, identified by L. W. Stephenson.

Leda sp. (numerous)
Ostrea sp. (small)
Exogyra sp. (right valve of very young individual)
Trigonia sp. (internal mold of young individual)
Pecten argillensis Conrad?
Pecten simplicius Conrad?
Crenella serica Conrad
Veniella conradi (Morton), (young individual)
Corbula sp.
Small smooth pelecypods of family *Veneridae*
Internal molds of small gastropod, possibly *Turritella*

Of the forms listed, Stephenson states, *Exogyra* sp., *Trigonia* sp., *Pecten argillensis* Conrad ?, *P. simplicius?*, *Crenella serica* Conrad, and *Veniella conradi* (Morton), are of Ripley Cretaceous age. And he adds:

This appears to be the first record of Cretaceous fossils in Missouri. The only other marine Cretaceous invertebrate recorded from the northern end of the Mississippi embayment is *Exogyra cancellata* Stephenson, reported to have been found in an excavation for a pier of the Illinois Central Railroad bridge over the Ohio River, near Cairo, Ill.; this specimen is preserved in the State Natural History Museum (No. 8358) at Springfield, Ill.[2]

The material collected from the glauconitic bed by Farrar, January, 1933, contained the following Clayton (Eocene) forms, identified by Julia Gardner.

Cucullaea cf. *macrodonta* Whitfield
Venericardia sp.
Turritella cf. *T. mortoni* Conrad
Turritella cf. *T. humerosa* Conrad

The following Clayton forms were identified by Julia Gardner in the material collected from the glauconitic bed by Stephenson, McQueen, and Farrar, March 29, 1933.

Pelecypoda
- *Leda* sp.
- *Cucullaea macrodonta* Whitfield
- *Nemodon?* (perhaps reworked from Cretaceous below)
- *Ostrea* sp.
- *Trigonia?* (perhaps reworked from Cretaceous below)
- *Venericardia* sp. (coarsely ribbed)
- *Venericardia* sp. (small)
- Lucinoid shell
- *Corbula* sp.

Gastropoda
- *Turritella humerosa* Conrad

The material collected from the Ripley sand beneath the glauconitic bed by Stephenson, McQueen, and Farrar, March 29, 1933 (U.S.G.S. Coll. 16,429) contained the following forms, identified by Stephenson.

Pelecypoda
- *Leda longifrons* Conrad
- *Glycymeris* sp.
- *Trigonia angulicosta* Gabb
- *Trigonia* aff. *T. enfaulensis* Gabb
- *Pecten argillensis* Conrad?
- *Lima* aff. *L. acutilineata* (Conrad)
- *Crenella serica* Conrad
- *Liopistha protexta* Conrad
- *Crassatellites* aff. *C. vadosus* (Morton)
- *Cardium* (*Criocardium*) *tippanum* Conrad
- *Cardium* (*Criocardium*) sp.
- *Aphrodina* sp.

Gastropoda
- *Acmaea* (?)
- *Anchura* (?)
- *Turritella* cf. *T. tippana* Conrad

Cephalopoda
- *Scaphites* sp.
- *Hamites?*

Arthropoda
- Crab claws

[2] L. W. Stephenson, "Species of Exogyra from the Eastern Gulf Region and the Carolinas," *U. S. Geol. Survey Prof. Paper 81* (1914), p. 55.

Cyprimeria alta Conrad (?)
Legumen ellipticum Conrad
Tenea pinguis Conrad
Unidentified pelecypods

The outcrop of fossiliferous Ripley sand on top of Crowleys Ridge is described as follows: road ditch about 150 feet south of road junction, near southeast corner of SE. ¼ Sec. 4, T. 27 N., R. 11 E., about a mile in air line northwest of Ardeola, Stoddard County, Missouri; elevation 480 feet above sea-level; ferruginous, argillaceous sand overlain by poorly exposed glauconitic clay of Clayton formation.

The material collected at this locality by Stephenson, McQueen, and Farrar, March 29, 1933 (U.S.G.S. Coll. 16,430) contains the following forms identified by Stephenson.

Pelecypoda
Leda sp.
Nemodon sp.
Trigonia sp.
Pecten cf. *P. hilgardi* Stephenson
Pecten simplicius Conrad?
Pholadomya?
Liopistha protexta Conrad

Gastropoda
Turritella cf. *T. tippana* Conrad
Crassatellites sp.
Cardium (*Criocardium*) sp.
Tenea pinguis Conrad?
Legumen ellipticum Conrad
Leptosolen biplicata (Conrad)
Linearia sp.
Corbula sp.
Cephalopoda
Two small unidentified ammonites

F. E. MATTHES[3]

WASHINGTON, D. C.
June 24, 1933

CLASTIC FACIES AND FAUNAS OF MONTEREY FORMATION, CALIFORNIA

Confusion attending correlation of the Monterey, early upper Miocene of California, is referable in part to three prevailing beliefs. These are (1) that the formation is everywhere fine grained, (2) that it nowhere yields useful macrofossils, and (3) that its epeiric seas did not receive material from eastern lands which contributed to underlying and overlying formations.

Figure 1 is a sketch showing the formation as laid down. The shale facies is marine. The part sandy facies grades landward to include subaerial deposits, the strandward half of the clastic belt tending to be partly nonmarine. Considering its subaerial portions, the computed cubic content of sand and gravel in the Monterey is larger than that in the visible Vaqueros, and approximates that in the Temblor. The magnitude of this clastic component has been obscured by the fact

[3] Introduced by L. W. Stephenson.

that most of it lies in strandward territory and has been mapped under other names.

The idea that the Monterey formation is deficient in clastic facies has risen from the circumstance that at the type and other places

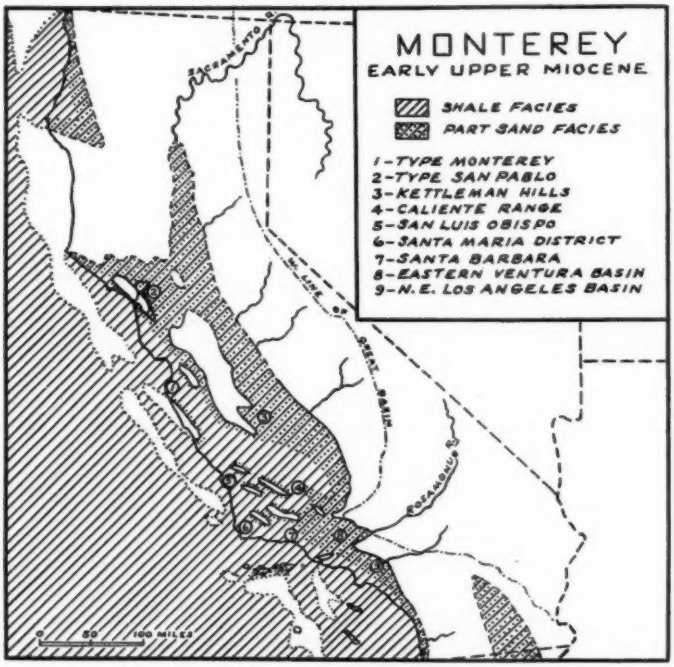

FIG. 1.—Monterey seas were widest in California Miocene, covering nearly all southern and middle Coast Ranges, Great Valley, and locally reaching Great Basin district on southeast. Clastic band (partly subaerial) underlying Great Valley is almost entirely concealed by later deposits, with result that Monterey has been described chiefly from fine-grained facies in Coast Ranges. Notice extensive clastic deposits near mouth of ancient Rosamond River which could have been derived only from Great Basin district.

where early examined it is prevailingly fine grained, these localities being far from the ancient continental strand. When strandward facies were subsequently mapped, the fact that these contain much sand and little of the typical shale caused investigators to call them by other names, to conclude that the Monterey was absent, or to restrict it to thin shale members. As a result, the Monterey became

known by that name where basinward facies prevail, as in the Santa Barbara, Santa Maria, Paso Robles, and typical districts, and known by other names in strandward areas where the sandy facies is present. Louderback[1] vigorously protested this practice 20 years ago, correctly recognizing that all of the Micoene formations become coarse grained strandward, but as he used the latter feature to further a thesis that the Miocene was indivisible into formations, the basic truth in his paper was overlooked. It is now becoming known that the Monterey consists largely of medium- and coarse-grained sediments near its continental strand. In intermediate areas the basal member is coarse and upper members prevailingly fine, due to the basal member having been deposited nearer, and upper members farther from, the ancient strand. Seaward the entire Monterey is commonly shale containing limestone and ash layers, the lower part being hard and siliceous, and the upper part soft and diatomaceous. Strandward the base is generally sandstone lying on Temblor sandstone. Thus, coarsely clastic facies near the ancient strand grade basinward to fine sand and silt, and finally to siliceous shale, diatomite, limestone, and ash.

Reed[2] has lately called attention to certain coarse facies, and it seems probable that the idea that the Monterey is exclusively shale will ultimately become extinct. That this idea still persists, however, is shown by the protests evoked when Goudkoff[3] recently assigned 700 feet of sand at Kettleman Hills to the formation.

The belief that the Monterey is barren of useful macrofossils is closely connected with the idea that it does not contain sand in appreciable amount. Sands of Monterey age yield fair macrofaunas at several localities, but whenever a clastic, fossiliferous facies is observed, the horizon is called by some other name. Near San Pablo Bay a thick clastic series has been divided on the basis of its macrofossils into three horizons; reading downward, the Santa Margarita ("Neroly"), Cierbo, and Briones. Since the Santa Margarita elsewhere in California rests, in some places conformably, on the Monterey, it is obvious that the Cierbo and Briones zones are faunal divisions of the latter formation. They are apparently confined to its upper half. As Clark, in his fine monograph[4] on the San Pablo group

[1] G. D. Louderback, "The Monterey Series in California," *California Univ. Dept. Geol. Bull.*, Vol. 7, No. 10 (1913).

[2] R. D. Reed, *Geology of California* (Amer. Assoc. Petrol. Geol., 1933), pp. 188, 190–194, 213, 224.

[3] P. P. Goudkoff, "Age of Producing Horizon at Kettleman Hills, California," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 15, No. 7 (July, 1931).

[4] B. L. Clark, "Fauna of the San Pablo Group of Middle California," *California Univ. Dept. Geol. Bull.*, Vol. 8, No. 22 (1915).

and elsewhere, has viewed the horizons as being characteristic and distinct, at least two divisions of the Monterey appear to be macrofaunally distinguishable.

In the Santa Monica Mountains an excellent succession of the upper two-thirds of the Monterey is exposed, divided into diatomite above, and siliceous shale with sandstone lenses below. The basal third of the Monterey is here represented by erosion and an interval of basic intrusion. According to Woodring[5] a macrofauna of 15 species from the lowest beds of the succession is slightly older than the Briones zone. A foraminiferal fauna secured by the writer from these beds has been determined by Boris Laiming as the zone of *Baggina californica*, the horizon of which is a few hundred feet above the base of the type Monterey. This correlates the horizon of Woodring's macrofauna as about one-third up in the formation as a whole. The Monterey thus has a third macrofaunal zone. As all three zones are apparently above the 2,000-foot basaltic base of the Monterey in Caliente Range, which yields *Turritella carrissaensis* and represents the interval of erosion and intrusion in the Santa Monica Mountains, a fourth and basal faunal zone is indicated. The basal zone of the Monterey is rarely mentioned in the literature: first, because it has few visible sediments, being commonly represented by unconformity and basic intrusion; second, because, having been laid down in an early, incipient sea, its visible sediments are generally sands which resemble those in the underlying Temblor; third, because one of its rare macrofossils, *Turritella carrisaensis*, resembles the common Temblor guide *Turritella ocoyana* and is easily confused with the latter when specimens are fragmental or worn.

The entire Monterey has sometimes been correlated with the Temblor, although the two are distinct formations commonly separated by unconformity. The break is as a rule a disconformity involving the absence of the basal Monterey, and is difficult to see owing to lack of angular discordance. From foraminiferal determinations it is known that the lowest strata at the type Monterey are not only stratigraphically above the highest bed of the type Temblor, but that an intermediate horizon not represented at the first-mentioned locality exists between. Although usually represented by unconformity, the intermediate horizon is locally depositional, as in the 2,000-foot coarse volcanic base of the thick Monterey section in Caliente Range. Confusion exists only in sections deficient in good foraminiferal faunas.

[5] H. W. Hoots, "Geology of the Eastern Part of the Santa Monica Mountains, California," *U. S. Geol. Survey Prof. Paper 165-C* (1930), quoting W. P. Woodring, p. 111.

For example, Hoots[6] has reported the Monterey form *Valvulineria californica* from Topanga (Temblor) beds. However, D. D. Hughes, who made the determination, informs the writer that the form was "poorly preserved, crushed, and not certain." The Monterey and Temblor are distinct in good successions.

The third prevailing belief, that the fine texture of the (basinward) Monterey is due to its sea having been cut off from lands on the east which contributed clastic material to underlying and overlying formations, has risen from a failure to consider adequately the distribution of seas and textures. When this distribution is analyzed the Monterey is seen to have a cubic content of clastic material equal to or exceeding that of these other formations. The texture of the Vaqueros and lower Pliocene formations is thought of as being coarse, the Temblor and Santa Margarita as fine and coarse, and the Monterey as fine, only because their deposits are studied at different distances from the continental strand. The fact that local coarseness or fineness of grain in all of them is primarily a function of the extent of their seas is seldom recognized. All are almost equally coarse grained within 10 miles of their nearest continental strand, have intermediate textures between 10 and 30 miles from such a strand, and are prevailingly fine grained at greater distances. Because the visible sediments of the Vaqueros and lower Pliocene formations were laid down in restricted arms of the sea, mostly within a few miles of land, the visible texture is prevailingly coarse. Limited areas of upper strata laid down farther from land are shales almost devoid of sand. The visible Temblor and Santa Margarita sediments were deposited in epeiric seas several times as large; hence, we see not only the coarse strandward band, but also broad, seaward stretches of shale. The Monterey epeiric sea was the widest of all, with the result that, while there is a similar clastic band strandward, this is overshadowed by vast stretches of the fine seaward facies deposited inland because of the maximum flooding. In the more studied districts, strandward (sandy) Vaqueros tends to be overlain by intermediate (sandy and silty) Temblor, which is in turn overlain by seaward (shaly) Monterey. We are prone to forget the relations, and to think of these textures as being characteristic instead of relative. The Monterey is not noticeably less clastic than other Miocene formations at equal distances from the continental strand.

Reed[7] follows the theory of isolation in his splendid volume on the

[6] *Op. cit.*, p. 99.

[7] *Op. cit.*, pp. 186, 188, 202–3, 224.

geology of California. Believing that the Monterey sea did not receive the usual amount of coarse particles, he postulates that rivers flowing from the east throughout Cretaceous, Eocene, Oligocene, and lower Miocene time were temporarily diverted into inland lakes during the Monterey stage, to again deliver coarse material in the Pliocene. He starts the diversion in Temblor time, when the seas were broadening, and ends it when the seas narrowed in the Pliocene, without noticing the implied textural relations. As previously explained the supposed paucity of coarse sediments in the Monterey is merely an appearance due to the fine-grained seaward facies being so widely exposed and over-obvious. It is requisite to the diversion hypothesis that the Tertiary deposits of the inland Mohave region be chiefly Miocene, and Reed so infers. In doing this he removes the Ricardo, with its *Pliohippus* and *Hipparion*, from the Pliocene, and places it in the Miocene. If the Ricardo is Pliocene, as its Equidae indicate, the evidence for a peculiarly upper Miocene interruption of communications becomes weak.

The supposed interruption of communications is not in accord with the marine deposition farther west. The vast content of ash and its siliceous derivatives in the seaward Monterey, comprising the bulk of several thousand feet of the shale facies, requires a source which is seemingly not available in coastal California with its minor basic flows and intrusions, and which is best looked for in the tremendous Cordilleran outpourings on the east. As the prevailing winds were from the sea, the delivery was by streams. In the north, streams from the Sierra Nevada contributed, but aid from the ancient Sacramento River by carrying ash from the Great Basin district is indicated. In the south, rivers carrying ash from this district appear to be a necessity. Reed cuts off the Great Basin district at the very time that its ash is needed to form the enormous siliceous deposits of the Monterey. The feature most opposed to disruption of communications is, however, that the coarsely clastic Monterey material arranged fan-like around the mouth of the ancient Rosamond River, and amounting to approximately 100 cubic miles, had no adequate source other than the Great Basin district, as the San Gabriel Range was then low and partly submerged (Fig. 1).

The solution of many problems awaits an accurate determination of the varying Tertiary strand line, and the relation of textural and faunal facies to this. Pending such determination, the writer advances the theses that the Monterey formation is not deficient in clastic facies, is not barren of useful macrofossils, and, except for a remarkable concentration of siliceous deposits and wide extent of epeiric seas,

does not differ fundamentally from other Miocene horizons of the California province.

J. EDMUND EATON

NORTH HOLLYWOOD, CALIFORNIA
June 26, 1933

STRUCTURE AND STRATIGRAPHY, KELSEY ANTICLINE, UPSHUR COUNTY, TEXAS

CORRECTION

In the article, "Structure and Stratigraphy, Kelsey Anticline, Upshur County, Texas," in the *Bulletin*, Vol. 17, No. 6 (June, 1933), p. 661, in the paragraph on the *Carrizo*, the last sentence should be, "Though the lithologic break is clear, no *unconformable* contacts with the Wilcox were noted in this area." Also the cut lines now printed below Figure 5 on p. 668 should be below Figure 6 on p. 669; the cut line below Figure 6 on p. 669 should be below Figure 7 on p. 670; and the cut lines below Figure 7 on p. 670 should be below Figure 5 on p. 668.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 17, NO. 8 (AUGUST, 1933), PP. 1016-1018

REVIEWS AND NEW PUBLICATIONS

Turkiye Petrol Madenleri (Petroleum in Turkey). By KEMAL LOKMAN. 134 pp. Ministry of Economy, Mining Dept., Ankara, Turkey. In Turkish.

This is a booklet of 134 pages containing useful information on petroleum in Turkey. It is divided into three parts. The first part gives a list of those who have investigated the oil possibilities of the republic together with their respective publications from 1899 to 1932. Next is given a brief geological description of the areas most talked of when oil possibilities in Turkey are mentioned.

The second part of the book includes interesting and complete data with tables and charts on the imports of petroleum and its derivatives into Turkey since 1923. It will be useful to reproduce the table of registered motor cars in the republic as of January 1, 1930.

Passenger cars	5,056
Trucks	2,579
Busses	204
Motorcycles	253

The total importation of 90,000 tons (630,000 barrels) of petroleum and its derivatives is divided as follows.

	Per Cent
Kerosene	36.25
Light oils	32.20
Gasoline	24.40
Crude oil	6.25
Miscellaneous	.90
	100.00

It is interesting to note that Russia has pushed ahead of all other competitors in the matter of importation of petroleum to the Turkish market, as shown by the following distribution of imports.

	Per Cent
Russian	46.85
Rumanian	28.65
U. S.	18.16
Others	6.34
	100.00

The third part contains extracts from the petroleum law of 1926 and lists the import duties. The duties range from 1 lira per 100 kilo or $0.66 (gold) per barrel on heavy crude and motor oils to 13.20 lira per 100 kilo or $8.71 (gold) per barrel on light oil and gasoline.

The book is well printed and well illustrated and will be undoubtedly of use to those interested in the petroleum industry of Turkey.

DJEVAD EYOUB

ANKARA, TURKEY
June 1933

RECENT PUBLICATIONS

CALIFORNIA

"Geology of San Miguel Island, Santa Barbara County, California," by Carl St. J. Bremner. *Santa Barbara Mus. Nat. Hist. Occas. Paper 2* (1933). 23 pp., 2 figs., 8 photos., 4 pls. 7×10 inches. Printed by the Museum, Santa Barbara.

CANADA

The following articles are published in the *Canada Geol. Survey Summary Rept. 1932* (Ottawa, 1933).

"Borings for Water, Oil, and Gas in British Columbia," by W. A. Johnston. *No. 2333*, Pt. A II, pp. 177–78.

"Birch Ridge Structure, Alberta," by G. S. Hume. *No. 2329*, Pt. B, pp. 68–74.

"Deep Borings in the Prairie Provinces," by W. A. Johnston. *No. 2329*, Pt. B, pp. 90–94.

"Borings in Eastern Canada," by W. A. Johnston. *No. 2330*, Pt. D, pp. 69–71.

GENERAL

A Textbook of Geology: Part II—Historical Geology, by Charles Schuchert and Carl O. Dunbar. 3d edit., largely rewritten. 551 pp., 332 figs., 35 pls., 12 tables. Cloth. 6×9 inches. John Wiley and Sons, New York (1933). Price, net, $4.00.

Die Permokarbonischen Eiszeiten (Permo-Carboniferous Glaciation), by Wilhelm Salomon-Calvi. 156 pp., 8 maps. 6¼×9¼ inches. Paper. Akademische Verlagsgesellschaft M.B.H., Leipzig (1933). Price, M. 13.80.

"Geology of Petroleum," by V. C. Illing. A report on the "Progress of Naphthology, 1932." *Jour. Inst. Petrol. Tech.* (London), Vol. 19, No. 116 (June, 1933), pp. 427–36.

"Field Technology," edited by B. J. Ellis. A report on the "Progress of Naphthology, 1932." *Jour. Inst. Petrol. Tech.* (London), Vol. 19, No. 116 (June, 1933), pp. 448–96.

GEOPHYSICS

"Geophysics," by Oscar Weiss. A report on the "Progress of Naphthology, 1932." *Jour. Inst. Petrol. Tech.* (London), Vol. 19, No. 116 (June, 1933), pp. 437–47.

"Some Observations Concerning Electrical Measurements in Anisotropic Media, and Their Interpretation," by C. and M. Schlumberger and E. G. Leonardon. *Amer. Inst. Min. Met. Eng. Tech. Pub. 505* (1933). 25 pp., 18 figs.

KANSAS

"Origin of Domes in Lincoln and Mitchell Counties, Kansas," by Kenneth K. Landes and J. W. Ockerman. *Bull. Geol. Soc. Amer.*, Vol. 44, No. 3 (June, 1933), pp. 529–40, 3 figs.

MONTANA

"Geology and Mineral Resources of North-Central Chouteau, Western Hill, and Eastern Liberty Counties, Montana," by W. G. Pierce and C. B. Hunt. *U. S. Geol. Survey Press Notice 72308* (June 20, 1933). 7 mimeog. pp. and 1 map. Includes oil and gas resources.

OKLAHOMA

"Estimate of the Gas Reserves of the Oklahoma City Oil Field, Oklahoma City, Oklahoma," by H. B. Hill and E. L. Rawlins. *U. S. Bur. Mines Rept. Investigations 3217* (June, 1933). In coöperation with the State of Oklahoma and the Oklahoma City Chamber of Commerce. 54 mimeog. pp., 15 figs., 13 tables.

PENNSYLVANIA AND NEW YORK

"Subsurface Devonian and Silurian Sections Across Northern Pennsylvania and Southern New York," by Charles R. Fettke. *Bull. Geol. Soc. Amer.* Vol. 44, No. 3 (June, 1933), pp. 601–60, 2 figs., 1 table.

TEXAS

"A Study of Subsurface Pressures and Temperatures in Flowing Wells in the East Texas Field and the Application of these Data to Reservoir and Vertical-Flow Problems," by C. E. Reistle, Jr., and E. P. Hayes. *U. S. Bur. Mines Rept. of Investigations* (Washington, D. C., May, 1933). Mimeographed. 17 pp., 14 figs.

"A Study of 'Bottom-Hole' Samples of East Texas Crude Oil," by Ben E. Lindsley. *U. S. Bur. Mines Rept. Investigations 3212* (May, 1933). 22 mimeog. pp., 7 figs.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 17, NO. 8 (AUGUST, 1933.) PP. 1019-1020

THE ASSOCIATION ROUND TABLE

MEMBERSHIP APPLICATIONS APPROVED FOR PUBLICATION

The executive committee has approved for publication the names of the following candidates for membership in the Association. This does not constitute an election, but places the names before the membership at large. If any member has information bearing on the qualifications of these nominees, he should send it promptly to J. P. D. Hull, business manager, Box 1852, Tulsa, Oklahoma. (Names of sponsors are placed beneath the name of each nominee.)

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BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 17, NO. 8 (AUGUST, 1933), P. 1021

Memorial

REICHIE S. STELFOX

Reichie S. Stelfox died at Houston, Texas, in June, 1932, at the age of 28. He was born at Austin, Texas, in 1904.

After attending the Agricultural and Mechanical College of Texas in 1921 and 1922, he was a student at the University of Texas in 1927, 1928, and 1929, majoring in geology. At college he was a member of the Sigma Chi fraternity.

Immediately after leaving college he worked a few months for the Shell Petroleum Corporation, Dallas, Texas. In September, 1929, he was employed by the Gulf Production Company at Houston, Texas, as assistant geologist, engaged in subsurface work in the Gulf Coast and later in the northern part of the East Texas geosyncline in the vicinity of Van. He carried on both surface and subsurface work in the southern part of the syncline. In 1931 he was employed by the United Production Company, Houston, as geological scout, stationed at Jackson, Mississippi. He became an associate member of The American Association of Petroleum Geologists in 1931.

His death came as a shock to his numerous friends, who admired him for his ability and winning personality.

P. B. LEAVENWORTH

HOUSTON, TEXAS
June 15, 1933

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 17, NO. 8 (AUGUST, 1933), PP. 1022-1024

AT HOME AND ABROAD

CURRENT NEWS AND PERSONAL ITEMS OF THE PROFESSION

R. E. SHERRILL has returned to the geological department of the University of Pittsburgh, Pittsburgh, Pennsylvania, after spending a year on leave of absence on the Eleanore Tatum Long fellowship, completing his work in structural geology for the Ph.D. degree at Cornell University, Ithaca, New York.

PAUL D. TORREY, geologist, Torrey, Fralich, and Simmons, Ltd., Bradford, Pennsylvania, has a paper in the mid-year number of *Petroleum Engineer* (Dallas, Texas) entitled, "Recent Developments in the Eastern Oil and Gas Fields."

HANS E. THALMANN, with Bataafsche Petr. Mij., in Sumatra, has published several papers on the nomenclature of *Foraminifera* in *Eclogae Geologicae Helvitiae* (Emil Birkhäuser and Cie., Basel, Switzerland), Vol. 25, No. 2 (1932).

R. C. BECKSTROM read a paper on "Oil fields of Russia and Other Foreign Countries," before the Mid-Continent Section of the Petroleum Division of the American Institute of Mining and Metallurgical Engineers, at Tulsa, Oklahoma, June 12.

The seventh annual field conference of the Kansas Geological Society is announced for September 3–7, 1933, by the conference committee, THOMAS H. ALLEN, J. L. GARLOUGH, and E. P. PHILBRICK. The trip is to be in the Ozark region of Missouri, Arkansas, and Oklahoma to study the pre-Pennsylvanian rocks. H. A. BUEHLER, state geologist of Missouri, will have charge in Missouri, GEORGE C. BRANNER, state geologist of Arkansas, will have charge in his state, and IRA H. CRAM, chief geologist of the southwestern division of the Pure Oil Company, will have charge in Oklahoma. It is planned to assemble at Joplin, Missouri, Saturday evening, September 2, to start early Sunday eastward down the geological section from Mississippian to pre-Cambrian, then southwestward back up through the section, ending Thursday noon, September 7, near Spavinaw, Oklahoma. Registration including the guide book will not exceed $10.00. The conference committee at 412 Union National Bank Building, Wichita, Kansas, will furnish detailed information.

Pre-publication announcement has been made of a comprehensive and authoritative book, *Oil and Gas Geology of the Gulf Coastal Plain of Arkansas*, recently completed by W. C. SPOONER, consulting geologist of Shreveport, Louisiana. Publication is dependent on the number of advance subscribers. Orders at $3.80 per copy should be sent to Parke-Harper Company, Box 1300, Little Rock, Arkansas.

M. A. HARRELL, formerly with the Sun Oil Company geological staff at Dallas, Texas, received the degree of Ph.D. at the University of Indiana last June. His address is Burton, Texas.

FREDERICK G. CLAPP, consulting geologist, 50 Church Street, New York, has returned from Persia, where he was invited by the Persian Government to confer in matters of petroleum. After leaving Teheran, he visited remote parts of Persia and Afghanistan on a private geological and archeological trip.

The officers of the Panhandle Geological Society, Amarillo, Texas, for 1933 are: ARCHIE KAUTZ, president; THOMAS C. CRAIG, vice-president; and EARLE N. ARMSTRONG, secretary-treasurer.

President FRANK R. CLARK spoke on "Origin and Accumulation of Oil," before the Kansas Geological Society, June 24. A. A. P. G. affairs were also discussed.

CARL WEIDMANN, geologist of Essen, Germany, is engaged in scientific exploration in Peru, pending a resumption of work in petroleum geology. His address is care of Otto Wertheimber de Bary, Hacienda Coapana, via Urcos, per Ard. Señor Fernando Emmel, Cuzco, Peru.

HARRY M. ANDREEN, of the geological department of the Carter Oil Company at Tulsa, Oklahoma, died June 23, at Woodside, California, where he was on leave of absence trying to regain his health.

"Leitz Wide Field Binocular Microscope," Bulletin 9 of E. LEITZ, INC., New York, is ready for distribution. It contains 16 pages and is illustrated. Instruments of interest to geologists are described.

MARCEL E. TOUWAIDE, formerly petroleum engineer and geologist in Borneo and Morocco is now mining gold for the Societé Minière de Bafwaboli, Opienge par Stanleyville, Belgian Congo.

R. E. RETTGER, formerly district geologist for the Sun Oil Company, at San Angelo, Texas, is now with the same company at San Antonio.

A. N. WINCHELL, professor of mineralogy at the University of Wisconsin, addressed the San Antonio Geological Society at their regular Monday noon luncheon, June 26. He discussed briefly some recent studies of heavy accessory minerals in igneous rocks.

GEORGE I. MCFERRON, geologist for the Adams Royalty Company, has been transferred from Tulsa, Oklahoma, to Houston, Texas. His address is 2402 Esperson Building.

RONALD K. DEFORD is working for the Argo Royalty Company, at present in West Texas and New Mexico.

WALTER M. BURRESS has changed his address from Tyler, to Houston, Texas. He may be addressed at Box 515.

WILLIAM L. CLARK, formerly of Norman, Oklahoma, is now employed by the Kessler Oil and Gas Company, Petroleum Building, Oklahoma City, Oklahoma.

ED. SHAKELY, geologist for the Shell Petroleum Corporation, has been transferred from St. Louis, Missouri, to McPherson, Kansas.

J. E. BRANTLY has an office at Room 1003 First National Bank Building, Dallas, Texas.

R. P. LOCKWOOD has changed his address from 1090 Eleventh Street, Golden, Colorado, to Lamar, Missouri.

JOHN R. SANDIDGE, recently assistant professor of micro-paleontology at Princeton University, has been appointed paleontologist for the Magnolia Petroleum Company and is stationed at the San Antonio, Texas, office.

W. I. INGHAM may be addressed at Hartman, Colorado.

E. T. MONSOUR, who for several years has been paleontologist for the Humble Oil and Refining Company, at Monterrey, Mexico, has been appointed chief paleontologist of the combined subsidiaries of the Standard Oil Company (New Jersey) in Mexico, and is making his headquarters in Tampico.

DORSEY HAGER, geologist, has changed his address from Aberdeen, Washington, to Dawson Springs, Kentucky.

VAUGHN W. RUSSOM, geologist for Sinclair Prairie Oil Company, has been transferred from Fort Worth, Texas, to Alexandria, Louisiana.

W. D. CHAWNER has changed his address from 969 East State Street, Ithaca, New York, to 874 Adelaide Drive, Pasadena, California.

ARTHUR E. DIETERT, formerly at Richmond, Kentucky, with the Empire Oil and Refining Company, has been transferred to Pratt, Kansas, and may be addressed at Box 660.

LYMAN C. REED, formerly of Bryan, Texas, is now with the Lago Petroleum Corporation, Apartado 172, Maracaibo, Venezuela, S. A.

RALPH HOWARD MITCHELL, of Woldingham, Surrey, England, has been engaged in geological surveying in Palestine for several months.

RAE PREECE, formerly stationed at Tulsa, Oklahoma, is geologist for the Devonian Oil Company in their new offices in the Smith-Young Tower, San Antonio, Texas.

J. BRIAN EBY, consulting geologist and geophysicist of Houston, Texas, is in Germany this summer, studying the North German salt-dome basin.

PAUL WEAVER, in charge of the geophysics department of the Gulf Production Company, Houston, Texas, presented a paper, "Drilling of Shallow Holes for Geological and Geophysical Prospecting," before the Houston Geological Society, June 29.

The following were appointed by President Frank R. Clark as additional Association delegates to the International Geological Congress at Washington, D. C., July 22–29: E. DEGOLYER, K. C. HEALD, O. B. HOPKINS, HUGH D. MISER, and DAVID WHITE.